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A Review of Ti-6Al-6V-2Sn Fatigue Behavior

Prepared by M. F. AMATEAU and E. G. KENDALL
Materials Sciences Laboratory

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Laboratory Operations
THE AEROSPACE CORPORATION

Prepared for SPACE AND MISSILE SYSTEMS ORGANIZATION
AIR FORCE SYSTEMS COMMAND
LOS ANGELES AIR FORCE STATION
Los Angeles, California

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FOREWORD

This report is published by The Aerospace Corporation, El Segundo, California, under Air Force Contract No. F04701-70-C-0059.

This report, which documents research carried out from 15 January 1970 through 1 May 1970, was submitted for review and approval to 1st Lt Jerry J. Smith, SMTAE, on 14 July 1970.

Approved

W. C. Riley
W. C. Riley, Director
Materials Sciences Laboratory

Publication of this report does not constitute Air Force approval of the report's findings or conclusions. It is published only for the exchange and stimulation of ideas.

Jerry J. Smith
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Project Officer

ABSTRACT

A compilation of Ti-6Al-6V-2Sn fatigue data is presented for a number of different material forms and conditions. Stress versus log cycles to failure (S-N) curves or master diagrams, or both, for annealed, solution-treated and aged (STA), and thermomechanically worked (TMW) material are included. Room-temperature and high-temperature data are presented. The data are organized according to material form, such as sheet, plate, rolled bar, forging, and extrusion. Crack-propagation behavior in air and salt water is also included. The general characteristics of Ti-6Al-6V-2Sn fatigue are discussed and compared with those for other titanium alloys.

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FIGURES (Continued)

FIGURES (Continued)

FIGURES (Continued)

FIGURES (Continued)

FIGURES (Continued)

I. INTRODUCTION

Considerable amounts of titanium alloy are used for missile and aircraft structures. For these applications, Ti-6Al-6V-2Sn is currently being considered. A full evaluation of the potential of this alloy for aerospace structures requires knowledge of its fatigue behavior in various material forms under different test conditions.

The fatigue properties can be expressed in terms of crack initiation and crack propagation. This division is significant because cracks or flaws can easily be introduced into structural materials during fabrication. The design life of flawed structures depends mainly on the crack propagation properties of the material. Even in the absence of flaws, high-stress or low-cycle fatigue reflects crack-propagation behavior because crack initiation accounts for only 5 to 30 percent of the life-to-failure under these conditions.

The majority of the Ti-6Al-6V-2Sn fatigue data is in the form of stress versus log cycles to failure (S-N) curves that do not distinguish between crack initiation and crack propagation. A small amount of information is available pertaining to crack propagation in Ti-6Al-6V-2Sn, but practically no data exist on crack initiation life.

The material conditions that influence the fatigue behavior of this alloy include processing variables, thickness, heat treatment, and oxygen content. The test variables that influence fatigue life include temperature, environment, specimen geometry, stress ratio, and type of loading. This report summarizes the available information pertaining to Ti-6Al-6V-2Sn fatigue behavior under a variety of material conditions and test variables.

II. COMPARISON OF Ti-6Al-6V-2Sn and Ti-6Al-4V MECHANICAL PROPERTIES

The significance of Ti-6Al-6V-2Sn fatigue behavior is best appreciated in the light of other mechanical properties, such as strength, ductility, and fracture toughness. It is appropriate to compare Ti-6Al-6V-2Sn and Ti-6Al-4V mechanical properties because the latter is the most widely used alpha-beta titanium alloy. Some important mechanical properties for these materials are given in Table I for the solution treated and aged (STA) and annealed conditions. It is evident from this table that in an equivalent heat-treatment condition the yield and ultimate strengths of Ti-6Al-6V-2Sn are greater than those for Ti-6Al-4V. However, yield and ultimate strengths of Ti-6Al-6V-2Sn in the annealed condition are similar to those of Ti-6Al-4V in the STA condition. The ductility, as measured by percent elongation, is somewhat less for Ti-6Al-6V-2Sn than for Ti-6Al-4V in the annealed condition but is the same in the STA condition. The plane-strain fracture toughness (K_{Ic}) of Ti-6Al-6V-2Sn is significantly less than that for Ti-6Al-4V, even when comparing Ti-6Al-6V-2Sn in the annealed condition to Ti-6Al-4V in the STA condition.

When compared on a strength/density basis, many Ti-6Al-4V strength properties are superior to Ti-6Al-6V-2Sn for equivalent heat-treatment conditions. Specific strength properties for sheet material of both alloys at low, room, and elevated temperatures are given in Table II. The low-temperature, specific tensile yield strength (F_{ty}/ρ) is essentially the same for both materials in either the STA or annealed conditions. The specific tensile ultimate strength (F_{tu}/ρ) of Ti-6Al-6V-2Sn is greater than that for Ti-6Al-4V in the annealed condition but less than that for the Ti-6Al-4V in the STA condition. The room-temperature (RT) specific tensile properties are greater for Ti-6Al-6V-2Sn than for Ti-6Al-4V, but the reverse is true for the compressive properties (F_{cy}/ρ). All of the high-temperature, specific strength properties of the Ti-6Al-6V-2Sn are superior to those of Ti-6Al-4V.

III. Ti-6Al-6V-2Sn FATIGUE LITERATURE

Scientific literature was searched to survey Ti-6Al-6V-2Sn fatigue data. The reference sources that were examined include Metallurgical Abstracts published jointly by ASM and the Institute of Metals and International Aerospace Abstracts published by the AIAA in cooperation with NASA. These sources cover both English language and foreign journals. Reference sources that cover government reports and information not available in open literature were also searched, including Scientific and Technical Aerospace Reports published by NASA and Technical Abstract Bulletins published by DOD. Additional references were obtained by direct contact with the Defense Metals Information Center and with the technical department of the Titanium Metals Corporation of America.

A total of 25 references were found that contained Ti-6Al-6V-2Sn fatigue information. Table III is a breakdown of the contents of these references. Most of the Ti-6Al-6V-2Sn fatigue data are for room-temperature, S-N behavior in air. The most numerous references found were for data on forgings in the STA condition. Considerably less data pertaining to high-temperature, S-N behavior are available, and no data were found for low-temperature behavior. Only three references were found that contained information on crack-propagation rate in either salt water or air. Of these, two presented the results in terms of stress intensity.

IV. ROOM-TEMPERATURE, S-N FATIGUE BEHAVIOR

Ti-6Al-6V-2Sn fatigue data are available for a variety of forms, heat-treatment conditions, thicknesses, and oxygen contents. Specific treatments and resulting properties are given in Table IV for the annealed condition, in Table V for the STA condition, and in Table VI for special TMV treatments. A number has been assigned to each material reported. This number will also be used for fatigue data presented in this report to identify the specific material. The material forms for which data have been accumulated include sheet, plate, bar, beta forgings, alpha-beta forgings, and extrusions. Although the chemical composition of each material reported is different, only the oxygen level is given in the tables, because it has the greatest effect on mechanical properties over the permissible range of variation. The complete chemical composition of the materials can be obtained from the original source.

A. ANNEALED CONDITION

Table VII is a summary of Ti-6Al-6V-2Sn fatigue strength in the annealed condition. The fatigue strength is influenced by the material form and the stress ratio (R). Figure 1 shows the maximum stress at 10^7 cycles for unnotched specimens and for notched specimens with stress concentration factors (K_T) of 3. The greatest fatigue strength for the annealed material occurs in the sheet form. Plate material has 20-ksi-less fatigue strength. Forged material appears to have the same fatigue strength as plate material. The fatigue strength of annealed extrusions may be 10 ksi below that of forgings and plate material. Sheet material also appears to have greater fatigue strength than plate in the notched condition, but the difference is not as great as in the unnotched specimens.

Some recent work at Grumman Aircraft Engineering Company (Ref. 18), indicates that the edge condition can affect fatigue life of annealed sheet. A significant improvement of fatigue life is found for sheet with filed rather than belt ground edges (Fig. 2).

For sheet material in the annealed condition, S-N data are given in Figs. 3 through 5. The scatter appears to be greatest for unnotched specimens with R = 0.1. Figure 6 is a master diagram (modified Goodman diagram) for annealed sheet material in the unnotched condition.

Figures 7 through 10 give S-N behavior of annealed plate for R ranging from -1 to 0.3 in the notched and unnotched condition. A slight but definite dependence of fatigue life on oxygen content of the material can be seen in Fig. 10 for the unnotched conditions. In the notched condition, the dependence was quite pronounced with the lower oxygen material having the greater fatigue strength. A master diagram for unnotched annealed plate is given in Fig. 11.

Stress versus log cycle to failure (S-N) of annealed forged material is given in Figs. 12 through 21. There is no significant difference in fatigue behavior for beta processed and alpha-beta processed forgings in the unnotched (Fig. 13) and notched (Fig. 19) conditions.

Figure 22 gives the unnotched, S-N behavior of annealed extrusions. This curve lies somewhere below that of annealed forged material of similar stress ratios (Fig. 7). Notched, S-N fatigue behavior for annealed extrusions from two different sources are given in Figs. 23 and 24. Figure 25 is the master diagram for annealed extrusions in the notched condition.

B. SOLUTION TREATED AND AGED (STA) CONDITION

The Ti-6Al-6V-2Sn fatigue strength at 10^7 cycles in the STA condition is given in Table VIII and Figs. 26 (unnotched) and 27 (notched, $K_T = 3$). For both the unnotched and notched data, no significant differences in fatigue life occur among the different processing forms.

For unnotched and notched ($K_T = 4.2$) specimens tested at R = 0.1, the S-N behavior of STA sheet is given in Fig. 28. Figures 29 and 30 give unnotched, S-N data from two difference sources for STA plate A difference of 20 ksi in strength between the two sources (Materials No. 16 and 17) can be seen when comparing the curves for R = 1. Similar differences in fatigue behavior between these materials can also be seen in the master diagrams (Figs. 31 and 32). Figure 33 is an S-N curve, and Fig. 34 is a master diagram for notched specimens of STA plate material.

The effect of oxygen on the fatigue behavior of STA sheet is given in Fig. 35 for both unnotched and notched ($K_T = 3.5$) specimens. A slightly higher fatigue life is noted for the lower oxygen-content (0.11 percent) material compared with the higher oxygen-content (0.18 percent) material in the unnotched condition. In the notched condition, however, the fatigue life is significantly greater for the low-oxygen material. The sensitivity of notched fatigue strength to oxygen appears to be more severe in the STA condition than in the annealed condition (Fig. 10). The fatigue life in the longitudinal direction is somewhat greater than in the transverse direction of 1-in. thick STA plate (Fig. 35).

The unnotched, S-N behavior for thick (2-in.) STA plate appears to differ from that for the 1-in. STA plate. Figure 36 shows that the fatigue life at the higher stresses appears to be significantly less for the 2-in. plate for specimens tested in the longitudinal direction. The notched fatigue behavior appears to be similar for the two thicknesses.

The unnotched, S-N behavior of STA forgings tested in the longitudinal and transverse directions are shown in Fig. 37. Both low-oxygen and standard-oxygen materials were tested in the longitudinal direction and no significant difference was found. The transverse specimen may have a slightly greater fatigue life than the longitudinal specimen; however, sufficient data are not available to confirm this.

A difference in fatigue behavior for STA forgings of different oxygen content is apparent when tested in the notched condition. Figure 38 shows that in the life range between 10^4 and 10^7 cycles, the lower-oxygen content material has a greater notched fatigue strength.

Both beta-forged and alpha-beta-forged specimens have similar unnotched and notched fatigue behavior in the STA condition as shown in Fig. 39. This behavior is similar to that for annealed forgings. The unnotched and notched fatigue behavior of STA forgings tested at $R = -1$ are shown in Fig. 40. The S-N behavior for the material designated Strut Forging No. 2 (Material No. 32) was significantly different from that of the other materials tested. Microstructural examination of this material revealed bands of segregated beta structure (Ref. 22).

Figures 41 and 42 are an S-N curve and a master diagram, respectively. for unnotched specimens from STA forgings.

A limited amount of fatigue data is available for STA forgings tested under combined axial-tension and bending stress. S-N behavior for unnotched specimens with axial-to-bend stress ratios between 0 and 4 are given in Fig. 43.

The unnotched, S-N behavior of STA extrusions compared with plate and forged material are shown in Fig. 44 (Ref. 3). The scatter in this data does not permit definite conclusions to be drawn; however, a trend seems to indicate that the fatigue life of the extrusions is lower than that for forged and plate material. The same investigator found that the notched fatigue behavior for the three processing methods is comparable (Fig. 45). Additional notched fatigue data for STA extrusions are given in Fig. 46. Another investigator (Ref. 7), however, found that the fatigue behavior of STA extrusions was different from that of STA forged bar (Fig. 47). It is also evident from this figure that the fatigue behavior varied with the position in the extrusion.

C. THERMOMECHANICALLY WORKED (TMW) CONDITION

Table IX gives the fatigue strength of Ti-6Al-6V-2Sn that has been thermomechanically worked by forging at 1725°F, followed by water quenching (WQ) and aging at 1000°F for 4 hr before air cooling (AC).

The unnotched, S-N curves given in Figs. 48 and 49 are for low- and high-cycle behavior, respectively. The low-cycle fatigue tests were performed under a constant mean stress of 60 ksi. The unnotched fatigue behavior of Ti-6Al-6V-2Sn in the TMW condition is similar to that for the STA-forged condition in both the low- and high-cycle ranges.

The notched, S-N behavior of TMW forgings is given in Figs. 50 and 51 for the low- and high-cycle ranges, respectively. Figure 50 indicates that the TMW condition may result in a slightly greater low-cycle fatigue life than the standard STA forging.

V. HIGH-TEMPERATURE, S-N FATIGUE BEHAVIOR

Table X is a summary of Ti-6Al-6V-2Sn high-temperature fatigue behavior in both the annealed and STA conditions. The unnotched and notched S-N behavior of annealed sheet is given in Fig. 52. The notched fatigue behavior at 450°F is about 20 ksi lower than at room temperature in low-cycle range. At higher cycles, the difference between 450°F and room-temperature fatigue behavior decreases.

The fatigue behavior of annealed, hot-rolled bar at room temperature and at 600°F is given in Fig. 53, with and without 1 percent prestrain. Figure 54 gives the notched fatigue behavior of this material at room temperature and at 600°F.

The fatigue strength of annealed extrusions is practically identical at 400 and 600°F as shown in Figs. 55 and 56. Figure 57 is a single master diagram for annealed extrusions at both test temperatures.

The S-N behavior of STA forging at 300°F is given in Fig. 58 for unnotched specimens tested under a variety of combined axial and bending stresses. The fatigue behavior at 300°F is not too different from that at room temperature. The difference between room-temperature and elevated fatigue behavior becomes noticeable at 550°F for STA forgings (Fig. 59).

The notched fatigue properties of STA extrusions at 400 and 550°F are shown in Figs. 60 and 61. The differences in fatigue life for this material are noticeable only in the low-cylce region over the temperature range between room temperature and 550°F.

VI. CRACK-PROPAGATION BEHAVIOR

Crack growth for annealed sheet material is given in Fig. 62 for both air and salt water environments. These data show that the direction of testing, stress ratio, and environment have a significant effect on crack-growth behavior. The crack-growth rate in salt water is greater than that in air. In air, the greatest crack-growth rate occurs for the lowest stress ratio, while in salt water, the highest stress ratio results in a very rapid increase in growth rate with increasing stress intensity.

The effect of stress ratio on the crack-propagation rate (da/dN) of STA forgings in air was found to be consistent with the data on annealed sheet. Figure 63 shows that lower stress ratios resulted in greater crack-propagation rates, at least up to stress intensities of 18 ksi(in.)$^{1/2}$. The absolute growth rates of annealed sheet and STA forging, however, are quite different, as shown by a comparison of Figs. 62 and 63.

VII. COMPARISON OF Ti-6Al-6V-2Sn FATIGUE PROPERTIES WITH OTHER TITANIUM ALLOYS

The room-temperature, unnotched S-N properties of Ti-6Al-4V plate in the STA condition and Ti-6Al-6V-2Sn plate in the annealed condition for a variety of stress ratios are compared in Fig. 64. These data show that the fatigue properties of Ti-6Al-6V-2Sn exceed those of Ti-6Al-4V in the low-cycle range (to ~10^5 cycles), but the opposite is true in the intermediate cycle-range (10^5 to 10^7 cycles). This comparison is important because Ti-6Al-6V-2Sn in the annealed condition has mechanical properties similar to Ti-6Al-4V in the STA condition and can be considered as an alternative material in some applications. The room-temperature, unnotched S-N properties of STA forgings are compared for different titanium alloys in Fig. 65. In this case, Ti-6Al-6V-2Sn appears to be superior to Ti-6Al-4V over almost the entire cycle range. This conclusion also applies to the notched fatigue behavior of forged titanium alloys in the STA condition as shown in Fig. 66.

The room-temperature fatigue properties of STA extrusions are shown in Fig. 67 for unnotched specimens and in Fig. 68 for notched specimens. The unnotched fatigue life of Ti-6Al-4V exceeds that of Ti-6Al-6V-2Sn to just above 2 million cycles. The notched fatigue life of Ti-6Al-4V exceeds that of Ti-6Al-6V-2Sn over the entire cycle range.

Unnotched S-N fatigue data for STA Ti-6Al-4V and Ti-6Al-6V-2Sn forgings at 550°F are given in Fig. 69. Ti-6Al-6V-2Sn has the greater fatigue life.

The fatigue crack-growth behavior of a number of titanium alloys, including Ti-6Al-6V-2Sn and Ti-6Al-4V, is presented in Fig. 70. Almost all of the data fall within a single scatter band with the exception of Ti-6Al-6V-2Sn, which has a somewhat greater growth rate than the others. When tested in salt water, however, Ti-6Al-6V-2Sn appears to fall within the air-environment scatter band of the other titanium alloys (Fig. 71). This suggests that Ti-6Al-6V-2Sn has a lower crack-growth rate in salt water than in air. This conclusion is not consistent with other data reported in this report (Refs. 10 and 12).

VIII. CONCLUSIONS

Most of the Ti-6Al-6V-2Sn fatigue data are for room temperature, S-N behavior in air. Some high-temperature, S-N data (to 600°F) are also available, but no low-temperature results have been reported. Information pertaining to crack-propagation behavior in air and salt water is limited.

Both material form and thickness influence the fatigue properties of STA and annealed Ti-6Al-6V-2Sn. Sheet material has the highest strength, but plate and forgings have similar strengths. Extrusion material has a somewhat lower fatigue strength than plate and forging. Thick-plate specimens have a lower fatigue strength than thin-plate specimens.

Oxygen content in the range between 0.1 and 0.2 percent definitely effects fatigue properties. Longer fatigue life occurs in low-oxygen (0.1 percent) rather than in standard (0.16 percent) or high-oxygen (0.2 percent) material, especially in the notched specimens.

Fatigue strength at temperatures to 600°F is considerably lower than at room temperature in the low-cycle range (to 10^4 cycles). In the high cycle range, only relatively small differences in fatigue strength are found between room-temperature and high-temperature tests.

The crack-propagation rate of annealed and STA Ti-6Al-6V-2Sn in air depends upon stress ratio. The greatest crack-growth rate in air occurs at the lowest stress ratio.

There is conflicting data on the effect of salt water on the crack-growth rate of Ti-6Al-6V-2Sn.

Ti-6Al-6V-2Sn S-N behavior generally exceeds that for other titanium alloys, including Ti-6Al-4V.

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Table I. Comparison of Ti-6Al-6V-2Sn and Ti-6Al-4V Mechanical Properties

Property	Annealed Condition		STA Condition	
	Ti-6Al-6V-2Sn	Ti-6Al-4V	Ti-6Al-6V-2Sn	Ti-6Al-4V
Ultimate Strength, ksi[a]	155	125	170	160
0.2 percent Offset Yield Strength, ksi[a]	145	115	160	145
Elongation, percent	10	12	8	8
Plane strain fracture toughness (K_{Ic}), ksi/(in.)$^{1/2}$	35	105	31	55

[a] Based on minimum guaranteed properties (Ref. 24)

Table II. Sheet Ti-6Al-4V and Ti-6Al-6V-2Sn Strength-to-Density Ratios in STA and Annealed Conditions

Material	Heat Treatment	Temperature, °F	Strength-to-Density Ratio F_{ty}/ρ, 10^6 lb/in.	F_{cy}/ρ, 10^6 lb/in.	F_{tu}/ρ, 10^6 lb/in.
Ti-6Al-4V	Annealed: 1400°F	-100	1.00		1.06
		RT	0.75	0.89	0.81
		350	0.62	0.66	0.75
Ti-6Al-4V	STA: 1750°F for 1 hr, WQ; 1000°F for 4 hr, AC	-100	1.16		1.25
		RT	0.94	1.03	1.00
		350	0.75	0.85	0.91
Ti-6Al-6V-2Sn	Annealed: 1300°F	-100	1.01		1.10
		RT	0.88	0.87	0.94
		350	0.73		0.85
Ti-6Al-6V-2Sn	STA: 1650°F for 1 hr, WQ; 1050°F for 4 hr, AC	-100	1.16		1.22
		RT	0.98	1.00	1.04
		350	0.88		0.98

Table III. Amount of Ti-6Al-6V-2Sn Fatigue Data as Indicated by the Number of References

Material Condition	Material Form	Number of References: Room-Temperature S-N in Air	High-Temperature S-N in Air	Room-Temperature da/dN in Air and Salt Water
Annealed	Sheet	4	1	1
	Bar	1	1	0
	Plate	3	0	0
	Beta forging	1	0	0
	Alpha-beta forging	2	0	0
	Extrusion	2	1	0
STA	Sheet	1	1	0
	Bar	0	0	0
	Plate	3	0	0
	Beta forging	1	0	0
	Alpha-beta forging	7	1	1
	Extrusion	4	0	0
	Totals:	29	[illegible]	3

Table IV. Material Properties for Annealed Condition

Material No.	Material Form	Oxygen, percent	Thickness, in.	0.2 percent Offset Yield Strength, ksi	Ultimate Strength, ksi	Annealing Treatment	Reference No.
1	Sheet		0.060	148		1300°F for 2 hr, AC	10
2	Sheet	0.16	0.120	148	152	1300°F for 2 hr AC	4
3	Sheet	0.16	0.125	155	160	1300°F for 2 hr, AC	16
4	Plate	0.11	1.000	143	151	1350°F for 8 hr, AC	1 and 2
5	Plate	0.14	1.000	153	157	1300°F for 2 hr, AC	16
6	Plate	0.15	1.000	146	156	1300°F	21
7	Plate	0.18	1.250	142	150	1350°F for 8 hr. AC	1 and 2
8	Bar	0.16	1.000	153	160	1300°F for 2 1/2 hr, AC	9
9	Beta forging	0.16	2.000	143	152	1300°F for 2 1/2 hr, AC	17
10	Alpha-beta forging	0.16	2.000	151	160	1300°F for 2 1/2 hr, AC	17
11	Alpha-beta forging	0.16	4.000	137	147	1300°F for 2 hr, AC	4
12	Extrusion	0.13-0.17	0.300	145-157	132-140	1300°F for 1 hr, AC	23
13	Extrusion		0.750				20

Table V. Material Properties for STA Condition

Material No.	Material Form	Oxygen, percent	Thickness, in.	0.2 percent Offset Yield Strength, ksi	Ultimate Strength, ksi	Annealing Treatment	Reference No.
14	Sheet	0.15	0.125	177	181	1575°F for 1 hr, WQ; 1050°F for 4 hr, AC	16
15	Plate	0.11	1.000	163	170	1575°F for 1 hr, WQ; 1100°F for 4 hr, AC	1 and 2
16	Plate	0.16	1.000	171	177	1575°F for 1 hr, WQ; 1050°F for 4 hr, AC	16
17	Plate	0.15	1.000	179	188		21
18	Plate	0.18	1.250	152	162	1550°F for 1 hr, WQ; 1200°F for 4 hr, AC	1 and 2
19	Plate	0.17	2.000	166	176	1625°F for 1 hr, WQ, 1050°F for 4 hr, AC	1 and 2
20	Beta forging	0.18	1.250	178	190	1525°F for 1 hr, WQ; 1000°F for 4 hr, AC	19
21	Beta forging	0.16	2.000	173	185	1575°F for 1 hr, WQ; 1050°F for 4 hr, AC	17
22	Alpha-beta forging	0.11	0.560	169	181	1650°F for 1 hr, WQ; 1200°F for 4 hr, AC	12
23	Alpha-beta forging	0.11	1.375	158	165	1550°F for 2 hr, WQ; 1150°F for 4 hr, AC	7
24	Alpha-beta forging	0.16	1.375	163	171	1600°F for 2 hr, WQ; 1150°F for 4 hr, AC	7
25	Alpha-beta forging	0.12	1.875	165	169	1550°F for 1 hr, WQ; 1100°F for 4 hr, AC	12
26	Alpha-beta forging	0.16	2.000	173	185	1575°F for 1 hr, WQ; 1050°F for 4 hr, AC	17
27	Alpha-beta forging	0.11	2.500	153	163	1600°F for 1 hr, WQ; 1100°F for 4 hr, AC	5 and 6
28	Alpha-beta forging	0.16	2.500	176	182	1600°F for 1 hr, WQ; 1200°F for 4 hr, AC	5 and 6
29	Alpha-beta forging		3.000			1600°F for 2 hr, WQ; 1100°F for 8 hr, AC	15
30	Alpha-beta forging	0.15	5.250	168	178	1625°F for 1 hr, WQ; 1000°F for 8 hr, AC	22
31	Alpha-beta forging	0.15		179	185	1625°F for 1 hr, WQ; 1000°F for 8 hr, AC	22
32	Alpha-beta forging	0.15		174	183	1600°F for 1 hr, WQ; 1000°F for 8 hr, AC	22
33	Extrusion		0.500	162	174	1550°F for 1 hr, WQ; 1050°F for 4 hr, AC	3
34	Extrusion	0.13	0.750	160	171	1550°F for 1 hr, WQ; 1050°F for 6 hr, AC	7
35	Extrusion			159	170		8

Table VI. Ti-6Al-6V-2Sn Material Properties Given Special Thermomechanical Treatments

Material No.	Material Form	Oxygen, percent	Thickness, in.	0.2 percent Offset Yield Strength, ksi	Ultimate Strength, ksi	Annealing Treatment	Reference No.
36	Plate		1.00	120	1400	Spray quench after rolling	13 and 14
37	Beta forging	0.18	1.25	189	196	Forged at 1725°F, WQ; 1100°F for 4 hr, AC	19

Table VII. Ti-6Al-6V-2Sn Maximum Stress for 10^7 Cycles of Fatigue Life in Annealed Condition

Material No.	Material Form	Specimen Type	Stress Concentration Factor (K_T)	Stress Ratio (R)	Stress at 10^7 Cycles, ksi	Reference No.
3	Sheet	Unnotched	1.00	0.10	105	16
			1.00	0.25	110	16
2	Sheet	Notched	3.00	0.10	40	4
3	Sheet	Notched	4.20	0.10	28	16
5	Plate	Unnotched	1.00	-1.00	65	16
6			1.00	-1.00	60	21
			1.00	-0.30	73	21
			1.00	0.00	82	21
4 and 7			1.00	0.10	85	1
5			1.00	0.10	88	16
6			1.00	0.30	90	21
6	Plate	Notched	3.00	-1.00	18	21
			3.00	-0.30	28	21
			3.00	0.00	30	21
			3.00	0.30	35	21
4 and 7	Plate	Notched	3.50	0.10	28	1 and 2
11	Forging	Unnotched	1.00	-1.00	65	4
9 and 10			1.00	0.10	88	17
11			1.00	0.10	88	4
11	Forging	Notched	3.00	-1.00	28	4
			3.00	0.10	40	4

Table VII. Ti-6Al-6V-2Sn Maximum Stress for 10^7 Cycles of Fatigue Life in Annealed Condition (Continued)

Material No.	Material Form	Specimen Type	Stress Concentration Factor (K_T)	Stress Ratio (R)	Stress at 10^7 Cycles, ksi	Reference No.
9 and 10	Forging	Notched	4.00	0.10	30	17
11	Forging	Notched	5.00	-1.00	20	4
			5.00	0.10	35	4
12	Extrusion	Unnotched	1.00	0.10	75	23
13	Extrusion	Notched	2.58	0.06	33	20
12	Extrusion	Notched	2.76	-1.00	26	23
12	Extrusion	Notched	2.78	0.01	40	23
			2.78	0.43	60	23

Table VIII. Ti-6Al-6V-2Sn Maximum Stress for 10^7 Cycles of Fatigue Life in STA Condition

Material No.	Material Form	Specimen Type	Stress Concentration Factor (K_T)	Stress Ratio (R)	Stress at 10^7 Cycles, ksi	Reference No.
14	Sheet	Unnotched	1.0	0.10	114	16
14	Sheet	Notched	4.2	0.10	30	16
16	Plate	Unnotched	1.0	-1.00	80	16
17			1.0	-1.00	98	21
			1.0	-0.30	104	21
			1.0	0.00	110	21
16			1.0	0.10	108	16
15, 18, and 19			1.0	0.10	100	1 and 2
17			1.0	0.30	122	21
17	Plate	Notched	3.0	-1.00	20	21
			3.0	-0.30	28	21
			3.0	0.00	34	21
			3.0	0.30	42	21
19	Plate	Notched	3.5	0.10	25	1 and 2
15			3.5	0.10	40	1 and 2
18			3.5	0.10	30	1 and 2
21 and 26	Forging	Unnotched	1.0	0.10	104	17
28			1.0	0.10	88	5 and 6
27			1.0	0.10	95	5 and 6

Table VIII. Ti-6Al-6V-2Sn Maximum Stress for 10^7 Cycles of Fatigue Life in STA Condition (Continued)

Material No.	Material Form	Specimen Type	Stress Concentration Factor (K_T)	Stress Ratio (R)	Stress at 10^7 Cycles, ksi	Reference No.
28	Forging	Notched	3.0	0.10	25	5 and 6
24	Forging	Notched	3.3	0.10	44	7
23			3.3	0.10	35	7
22	Forging	Unnotched	1.0	0.30	108	12
20			1.0	0.04	125	19
20	Forging	Notched	3.5	0.33	30	19
30, 31, and 32	Forging	Unnotched	1.0	-1.00	94	22
30, 31, and 32	Forging	Notched	2.4	-1.00	60	22
30, 31, and 32	Forging	Notched	3.0	-1.00	40	22
29	Forging	Unnotched	1.0	-1.00	80	13
			1.0	0.20	118	13
			1.0	0.60	145	13
33	Extrusion	Unnotched	1.0	0.10	90	3
35	Extrusion	Notched	2.7	0.10	28	8
33	Extrusion	Notched	3.3	0.10	30	3
34			3.3	0.10	40	7

Table IX. Ti-6Al-6V-2Sn Maximum Stress at 10^7 Cycles of Fatigue Life for Thermomechanical Treatments

Material No.	Material Form	Specimen Type	Stress Concentration Factor (K_T)	Stress Ratio (R)	Stress at 10^7 Cycles, ksi	Reference No.
37	Forging	Unnotched	1.0	-1.0	70	19
37	Forging	Notched	3.5	-1.0	15	19

Table X. Ti-6Al-6V-2Sn Elevated Temperature Fatigue Life

Material No.	Heat Treatment	Material Form	Test Temperature, °F	Specimen Type	Stress Concentration Factor (K_T)	Stress Ratio (R)	Stress at 10^7 Cycles, ksi	Reference No.
14	Annealed	Sheet	450	Unnotched	1.00	0.10	96	16
			450	Notched	4.20	0.10	24	16
8	Annealed	Rolled bar	600	Unnotched	1.00	-1.00	40	9
			600	Notched	3.40	-1.00	20	9
			600	Notched	5.70	-1.00	10	9
			600	Notched	6.90	-1.00	15	9
			600	Notched	10.00	-1.00	10	9
12	Annealed	Extrusion	400	Notched	2.76	-1.00	25	23
			400	Notched	2.76	0.01	40	23
			400	Notched	2.76	0.43	60	25
12	Annealed	Extrusion	600	Notched	2.76	-1.00	18	23
			600	Notched	2.76	0.01	30	23
			600	Notched	2.76	0.43	60	23
29	STA	Forging	300	Unnotched	1.00	0.20	90	15
			300	Unnotched	1.00	0.60	145	15
28	STA	Forging	550	Unnotched	1.00	0.10	80	5 and 6
33	STA	Extrusion	400	Notched	2.70	0.10	31	8
33	STA	Extrusion	550	Notched	2.70	0.10	23	8

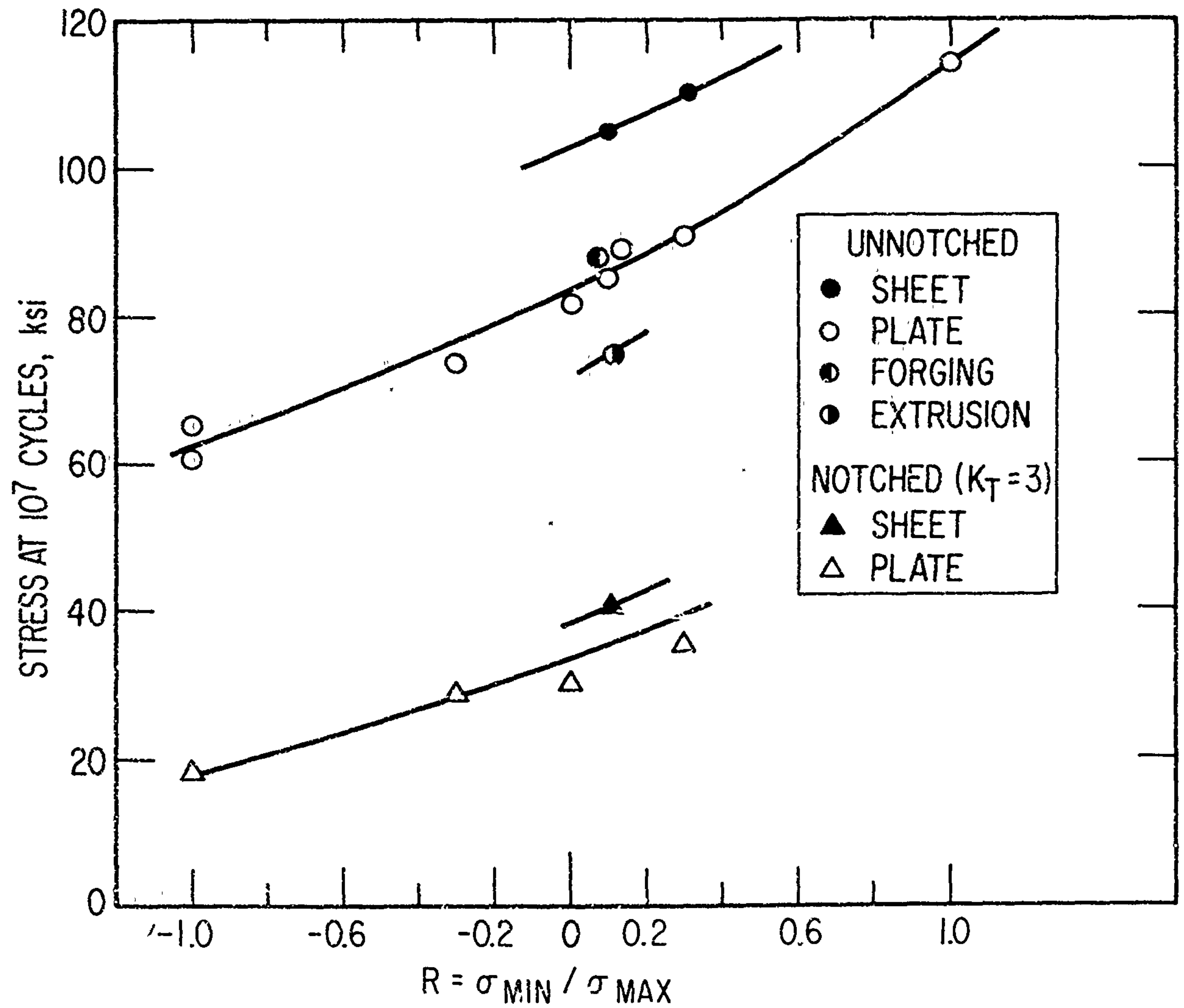


Fig. 1. Fatigue Strength for Annealed Ti-6Al-6V-2Sn

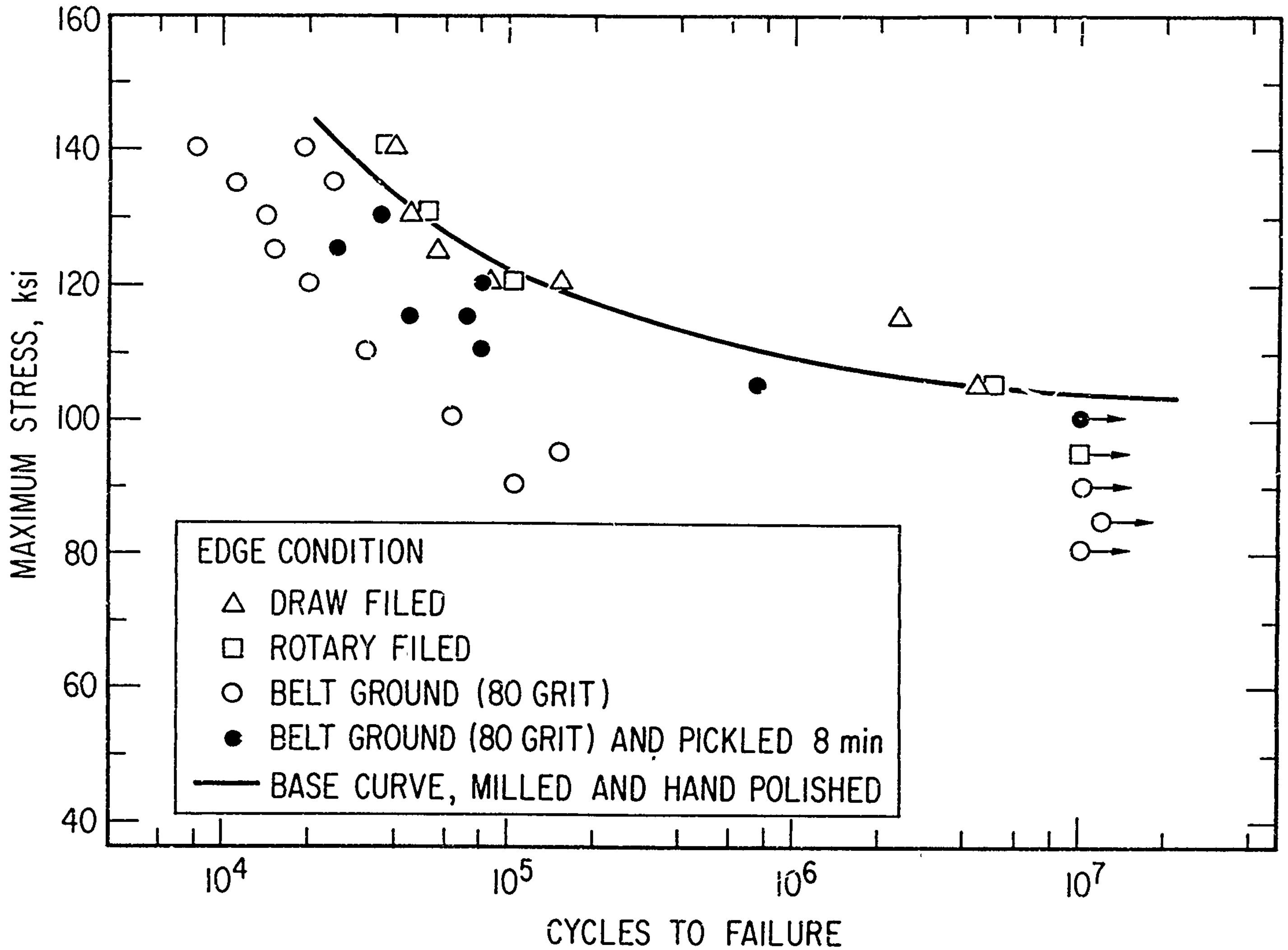


Fig. 2. Effect of Edge Condition on Unnotched, S-N Behavior of Annealed Sheet (R = 0.1, Material No. 3, Ref. 17)

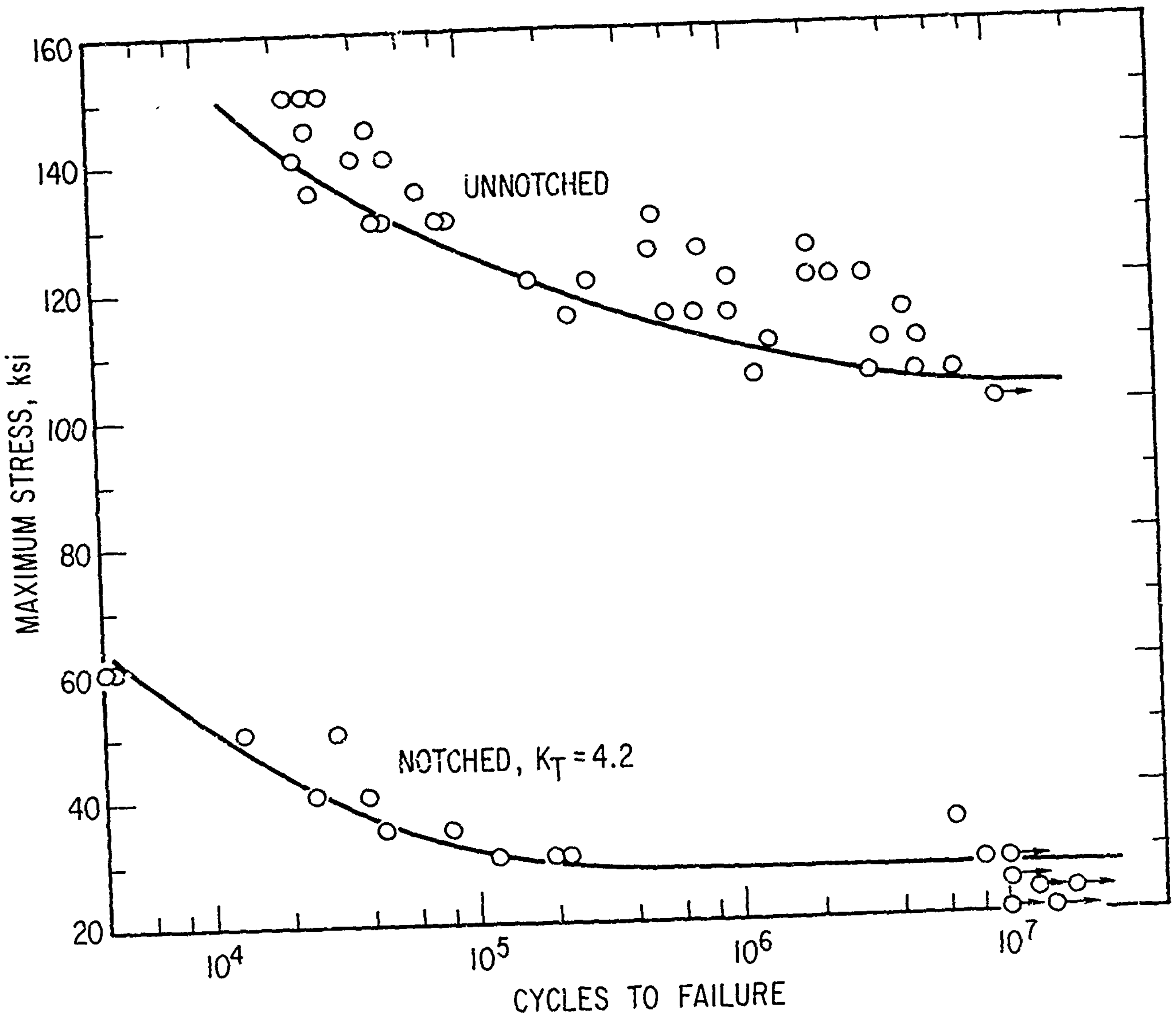


Fig. 3. Notched and Unnotched, S-N Behavior of Annealed Sheet (R = 0.1, Material No. 3, Ref. 15)

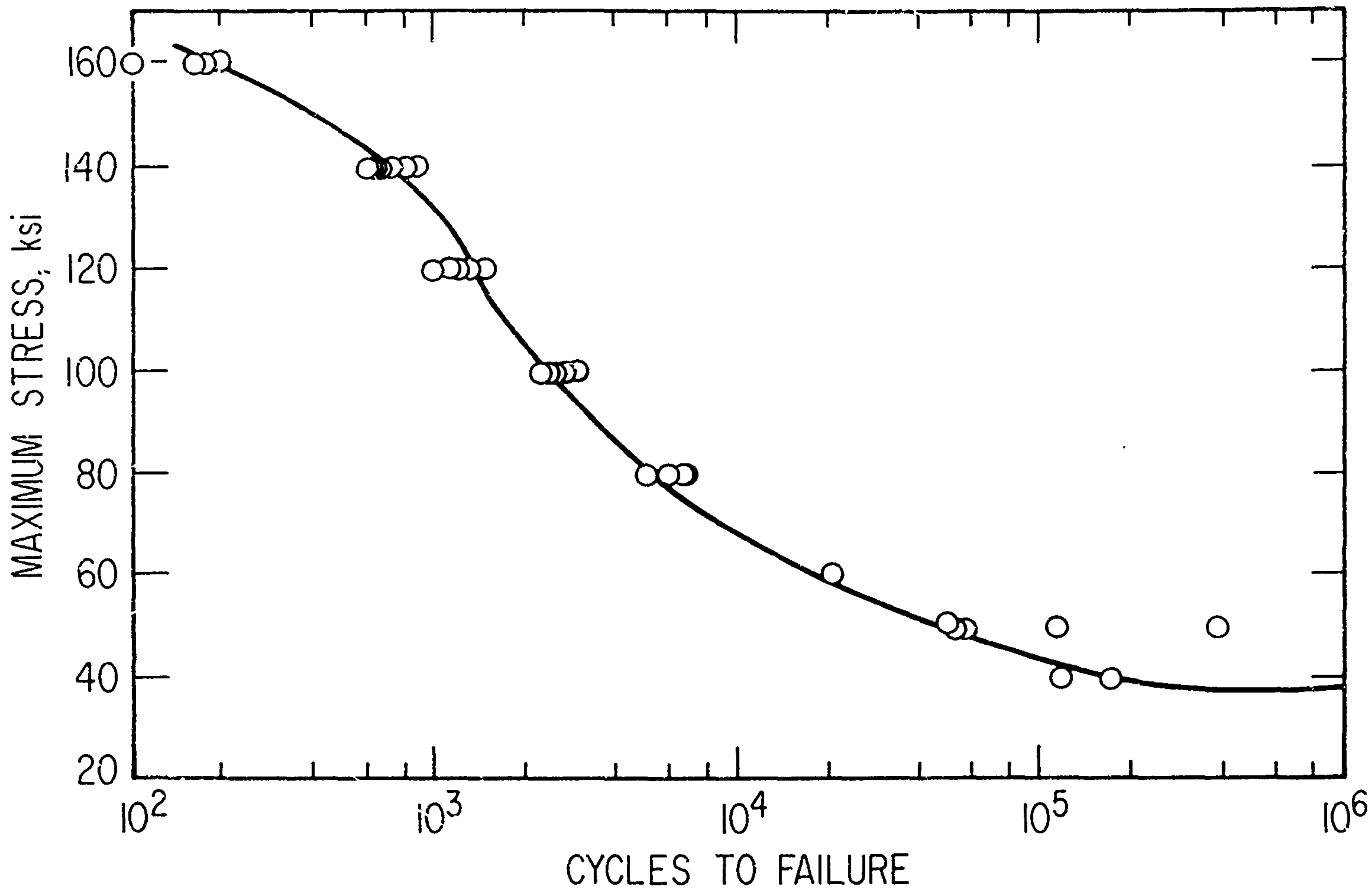


Fig. 4. Notched, S-N Behavior of Annealed Sheet (K_T = 3, R = 0.3, Material No. 2, Ref. 4)

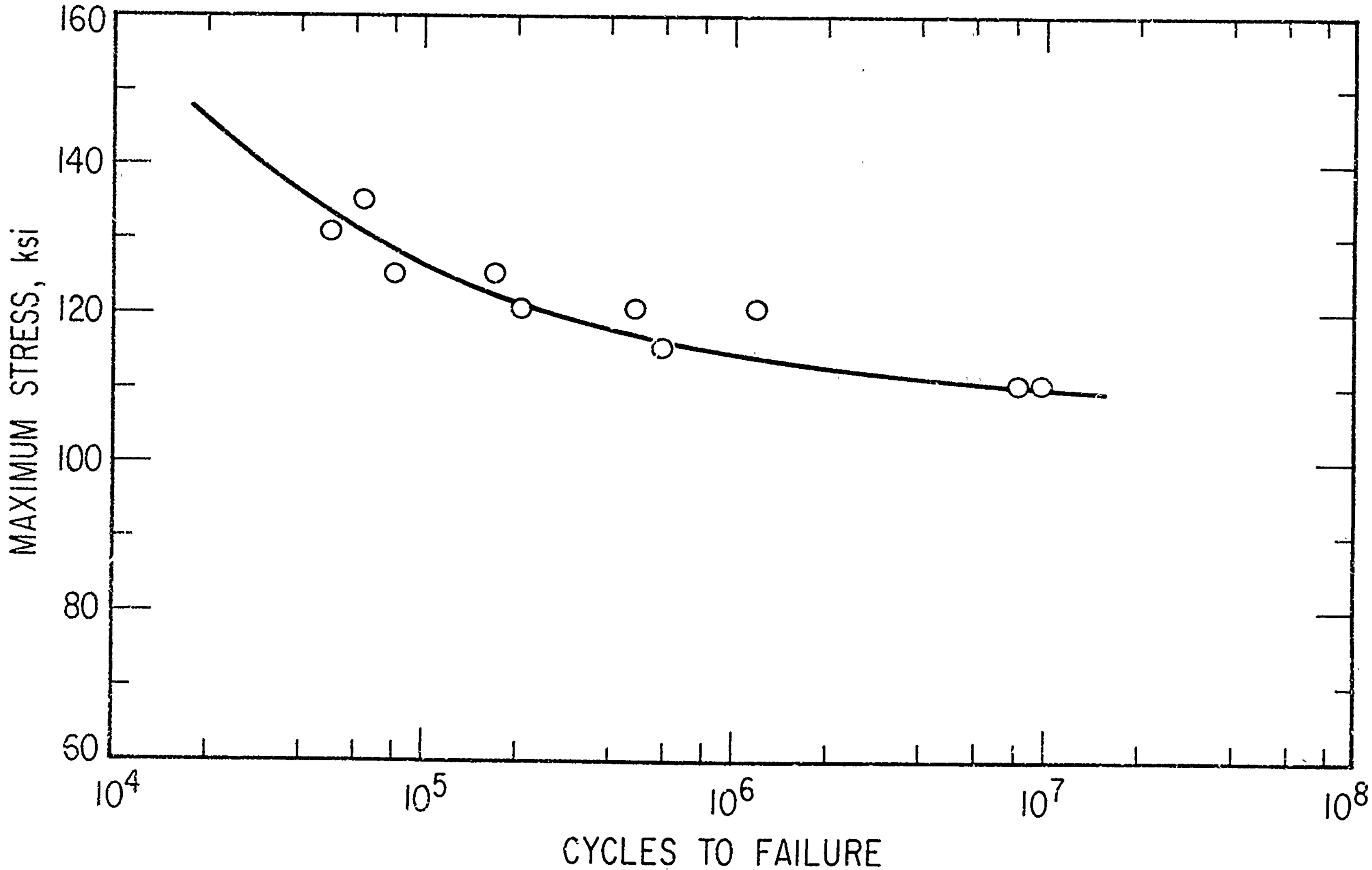


Fig. 5. Unnotched, S-N Behavior of Annealed Sheet (R = 0.25, Material No. 3, Ref. 15)

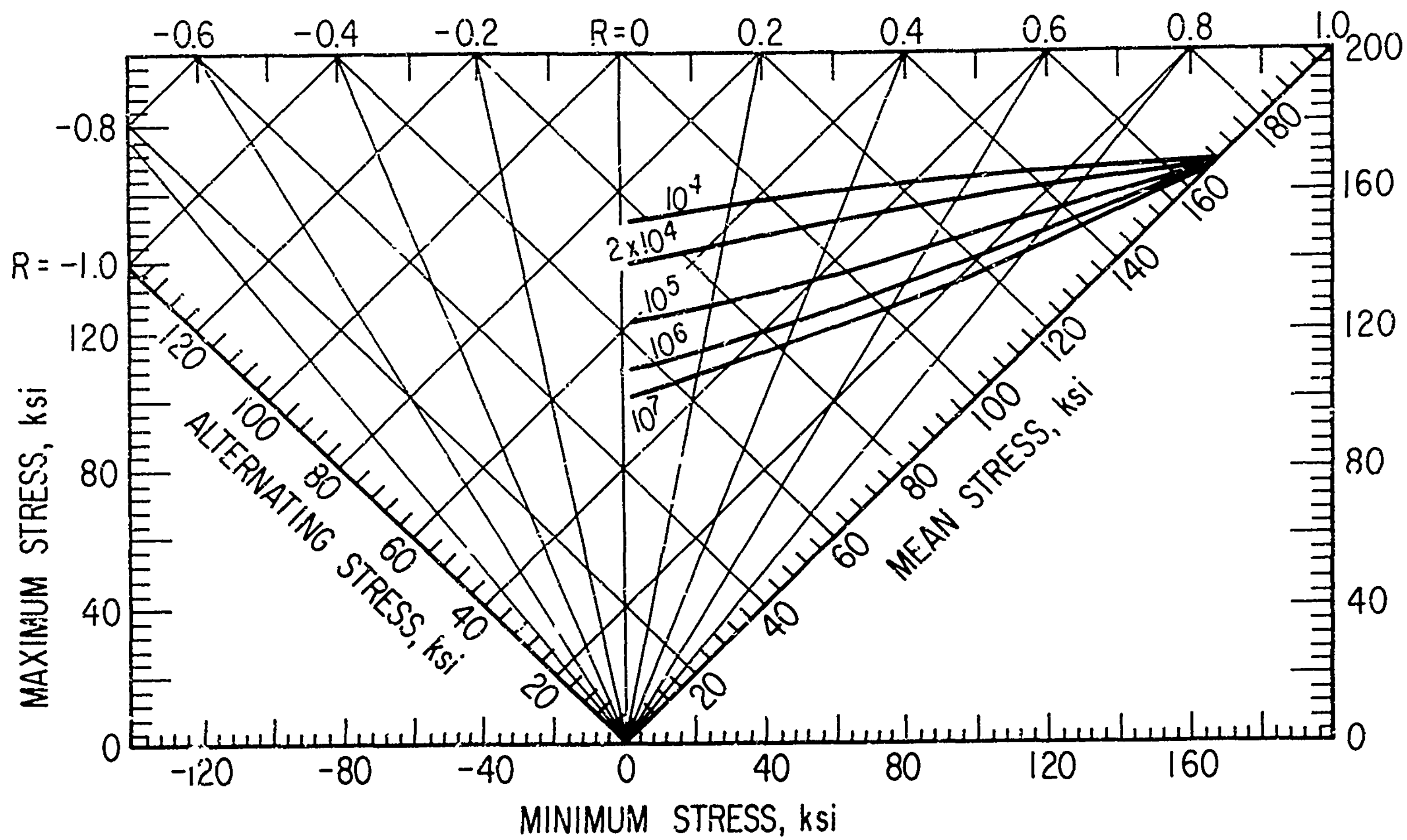


Fig. 6. Master Diagram of Unnotched, Annealed Sheet (Material No. 3, Ref. 15)

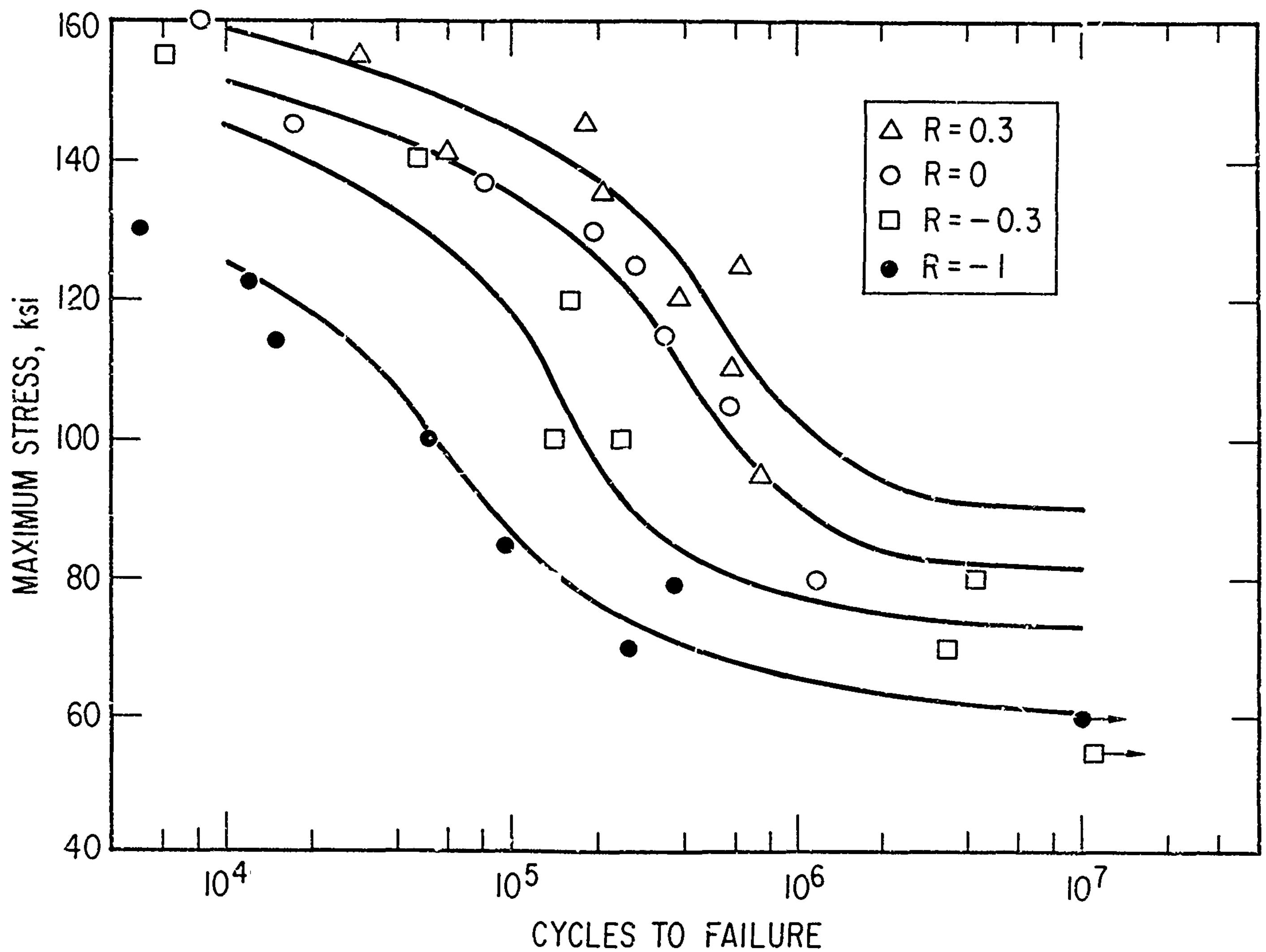


Fig. 7. Unnotched, S-N Behavior of Annealed Plate (Material No. 6, Ref. 20)

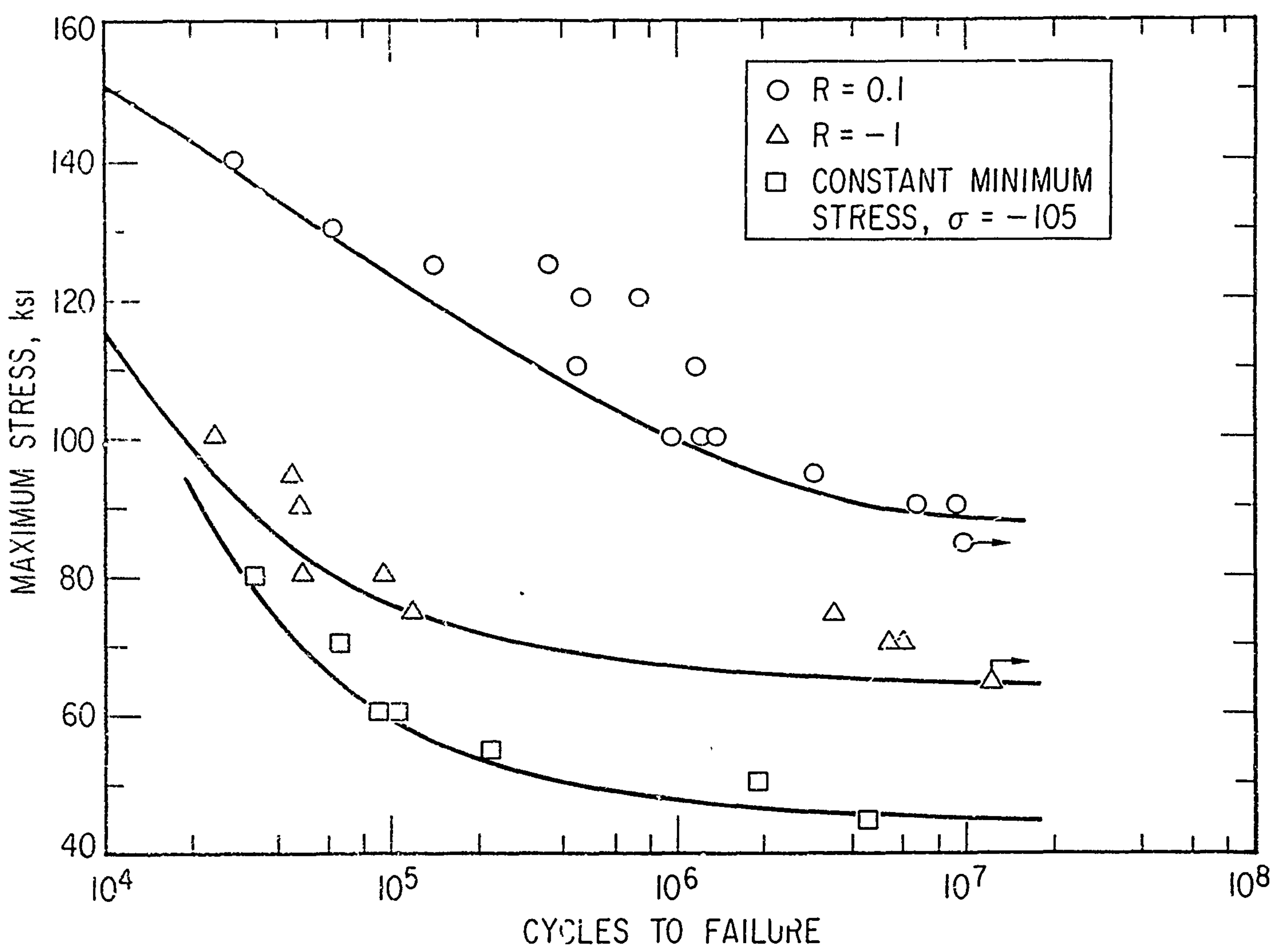


Fig. 8. Unnotched, S-N Behavior of Annealed Plate (Material No. 5, Ref. 15)

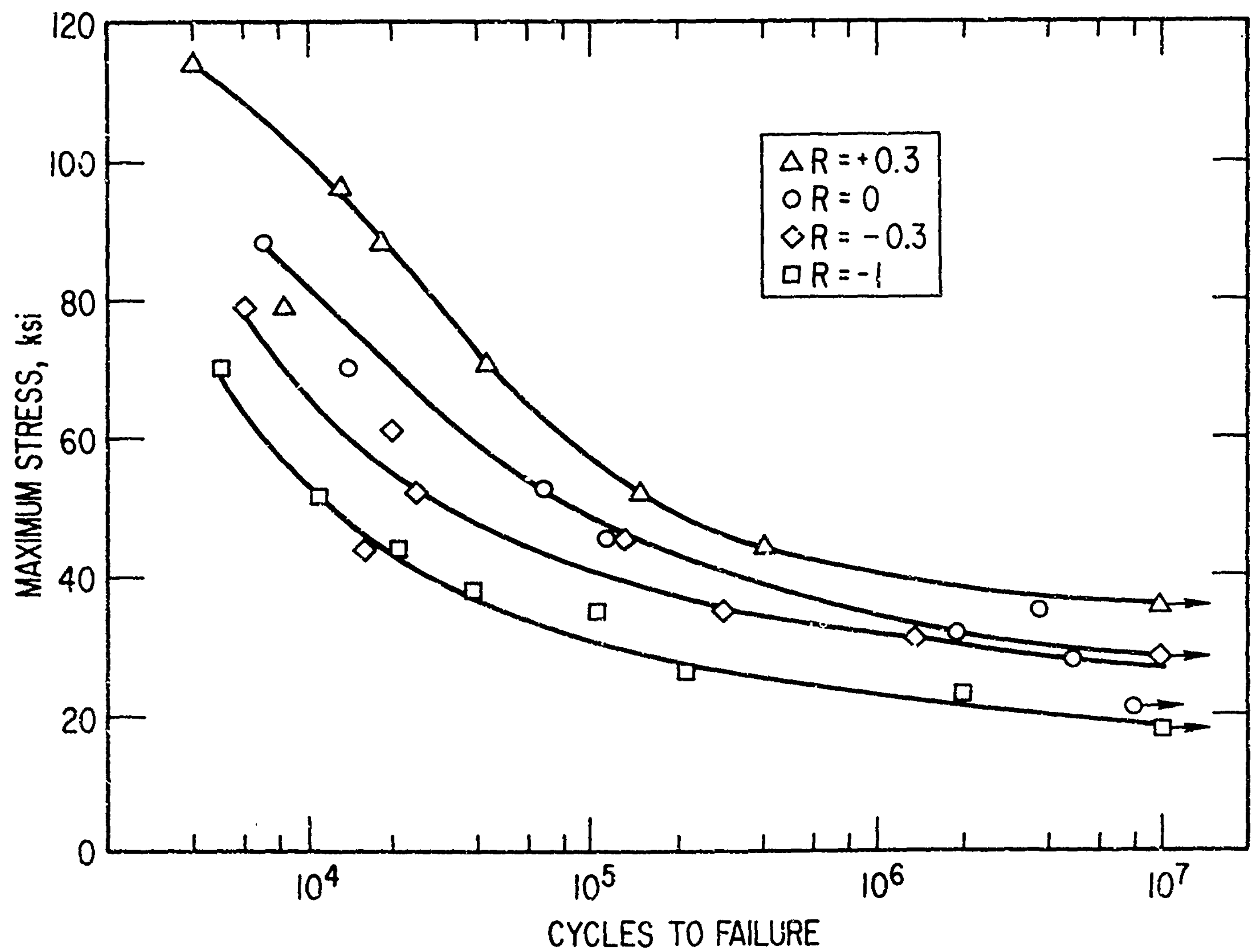


Fig. 9. Notched, S-N Behavior of Annealed Plate (K_T = 3, Material No. 6, Ref. 20)

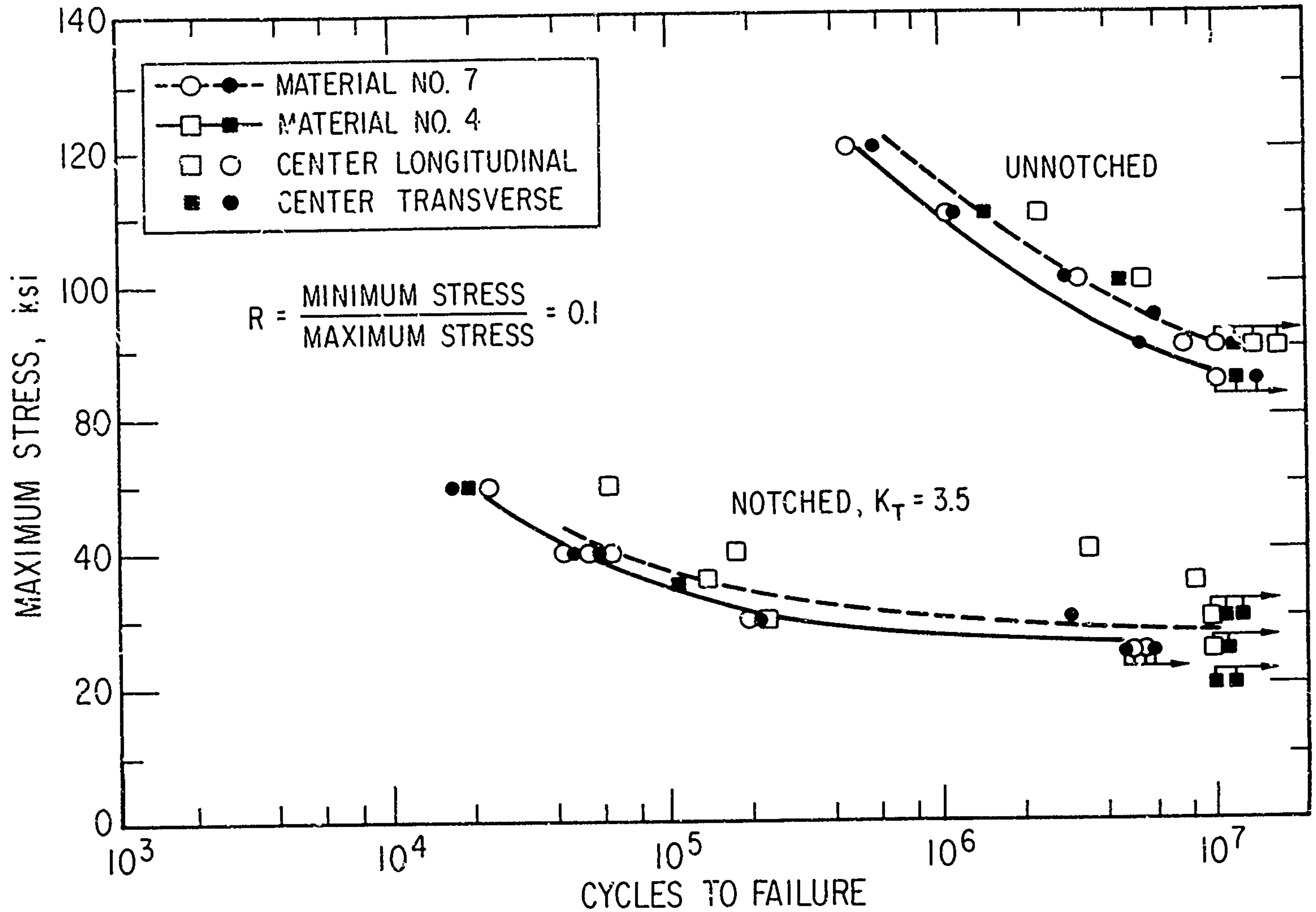


Fig. 10. Notched and Unnotched, S-N Behavior of Annealed Plate (Ref. 1)

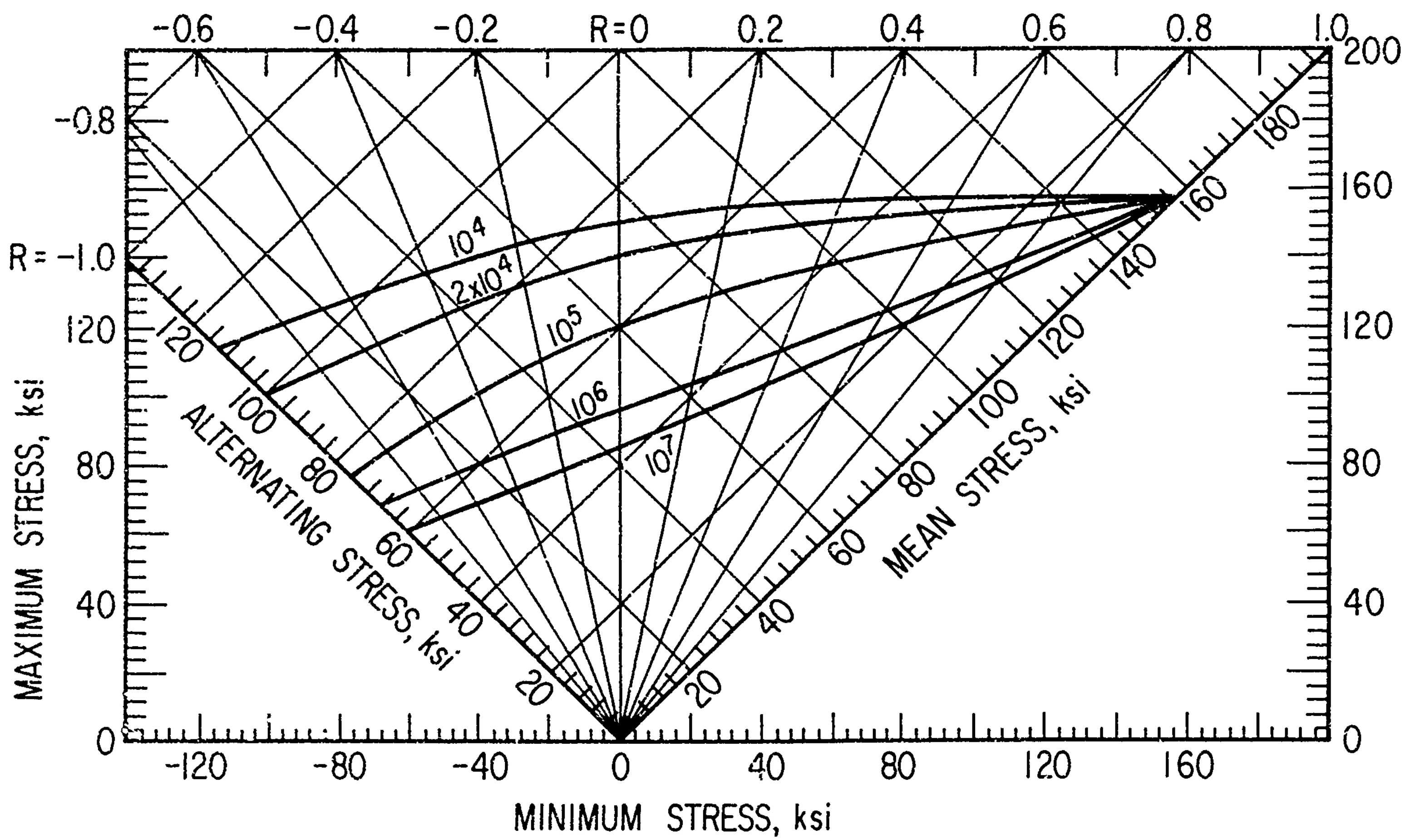


Fig. 11. Master Diagram of Unnotched, Annealed Plate (Material No. 5, Ref. 15)

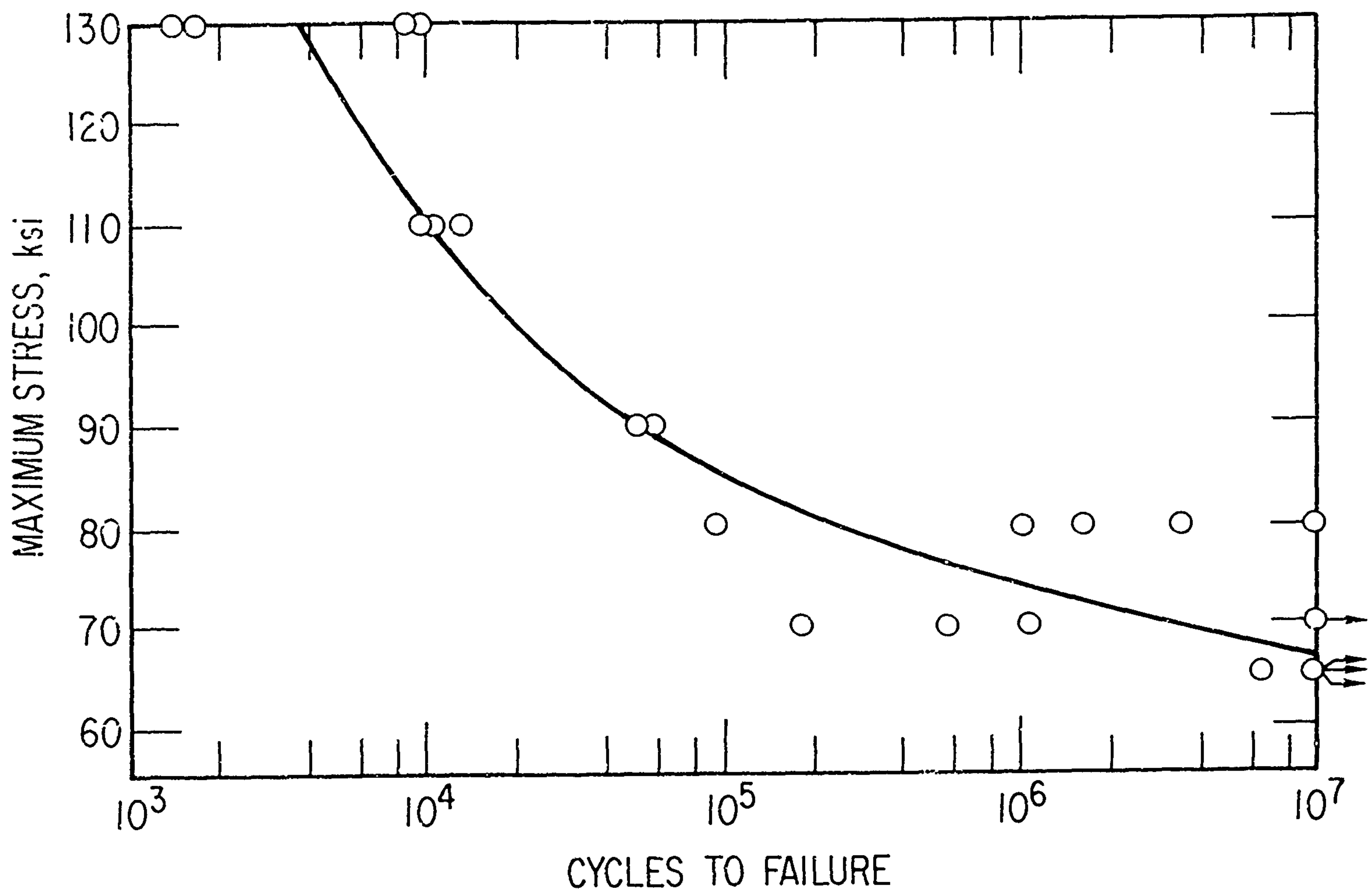


Fig. 12. Unnotched, S-N Behavior of Annealed Forgings Tested in the Longitudinal Direction (R = -1, Material No. 11, Ref. 4)

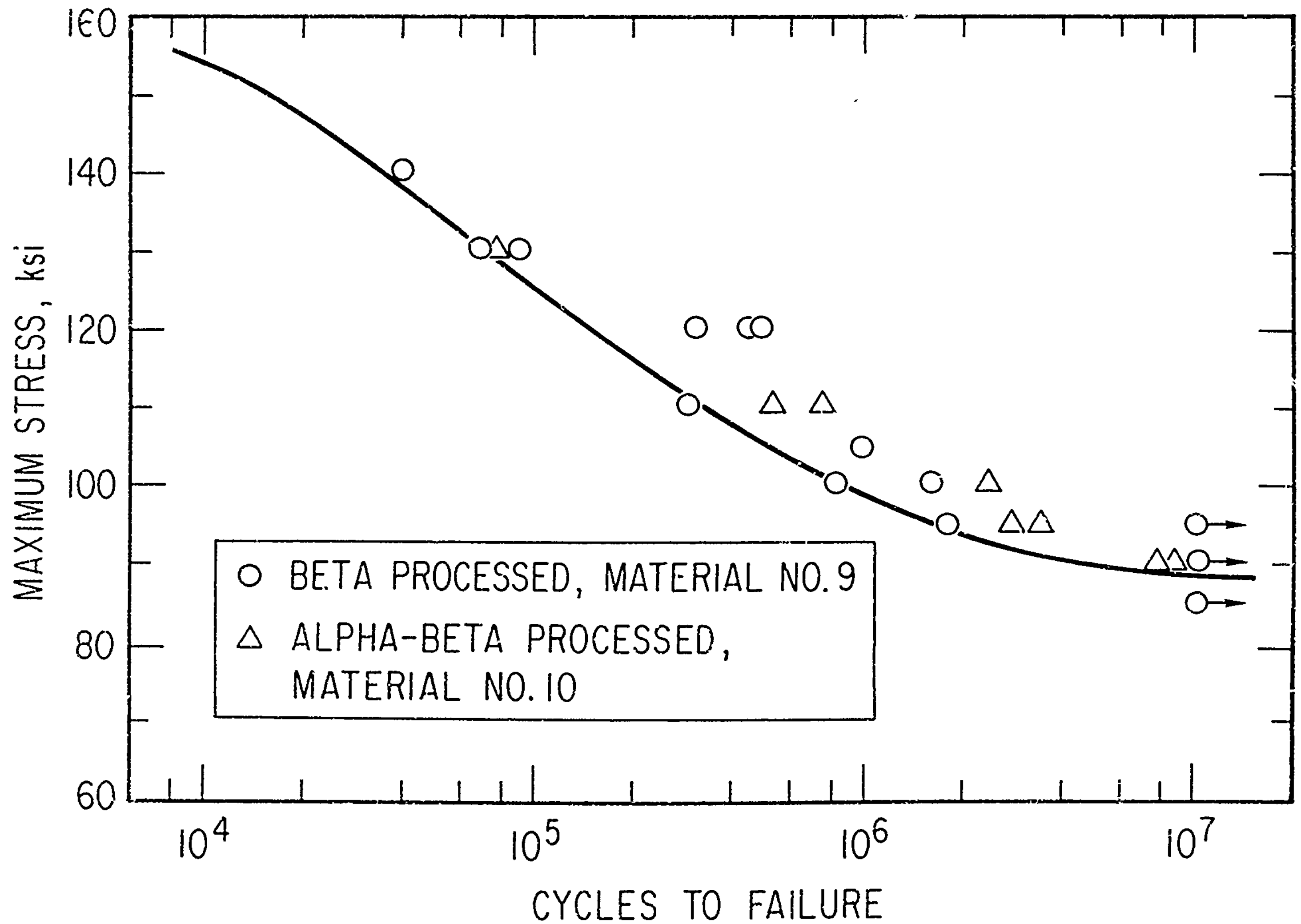


Fig. 13. Unnotched, S-N Behavior of Annealed Forgings Processed in the Beta and Alpha-Beta Fields (R = 0.1, Ref. 16)

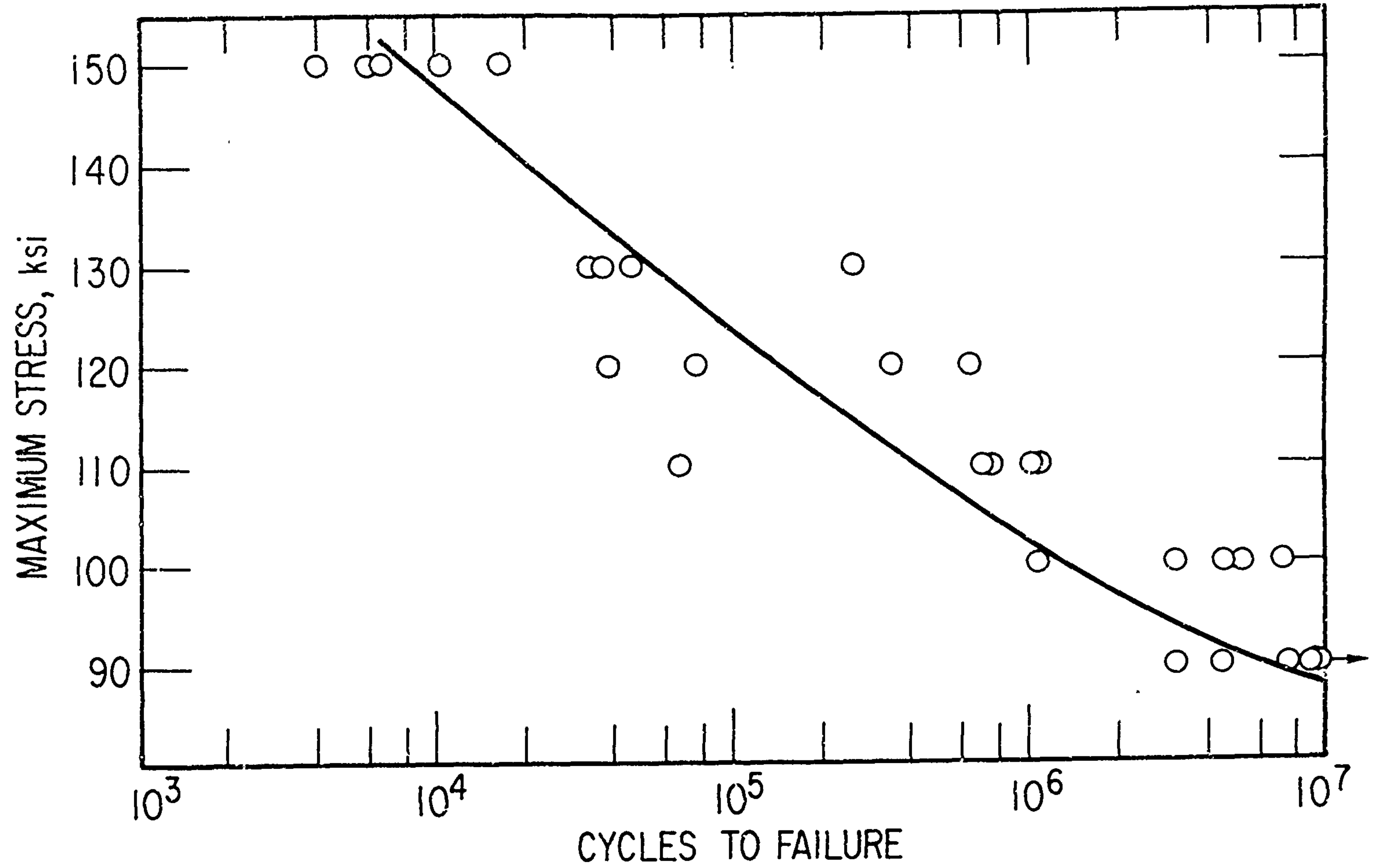


Fig. 14. Unnotched, S-N Behavior of Annealed Forgings Tested in the Longitudinal Direction (R = 0.1, Material No. 11, Ref. 4)

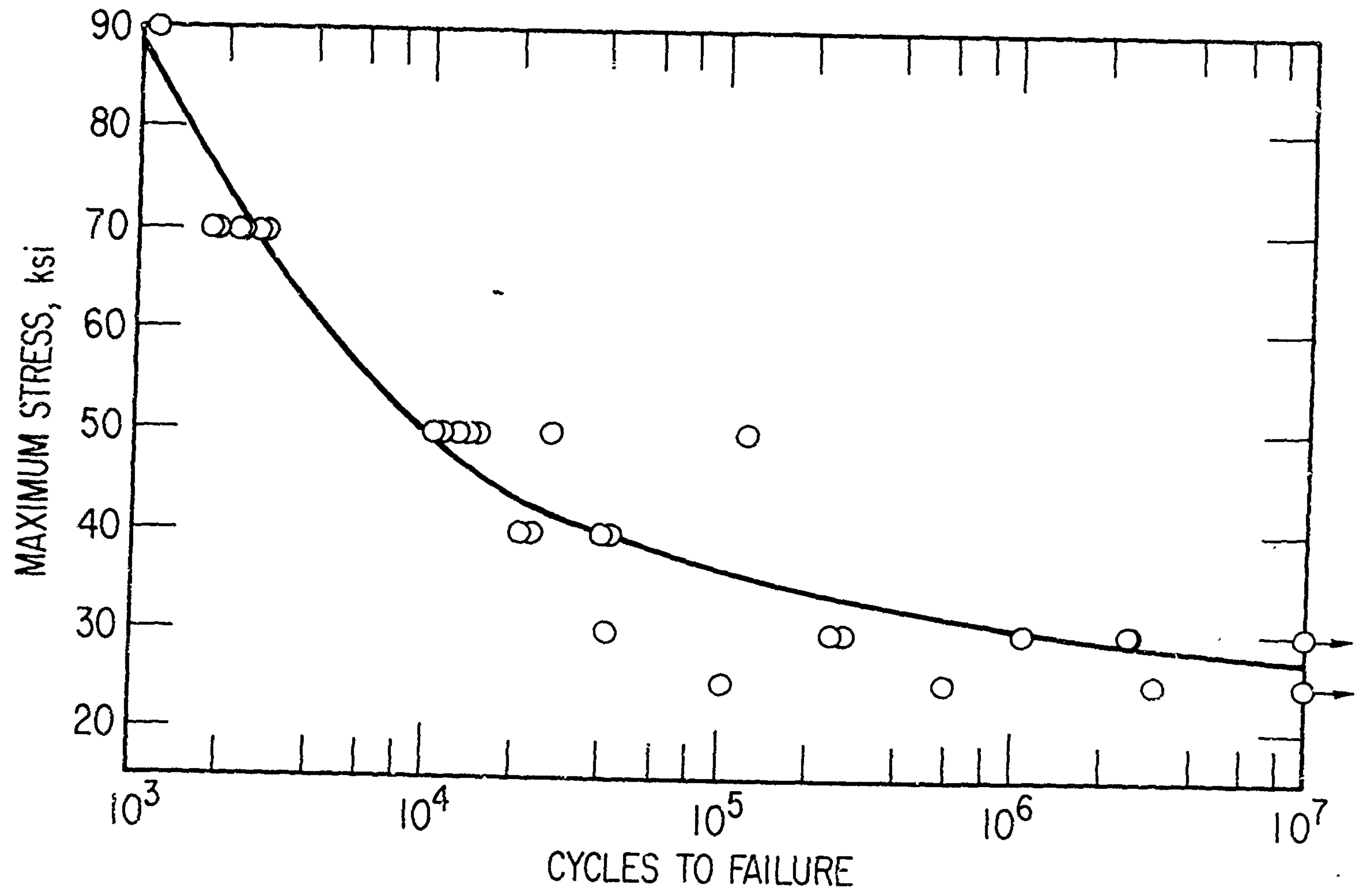


Fig. 15. Notched, S-N Behavior of Annealed Forgings Tested in the Longitudinal Direction ($K_T = 3$, $R = -1$, Material No. 11, Ref. 4)

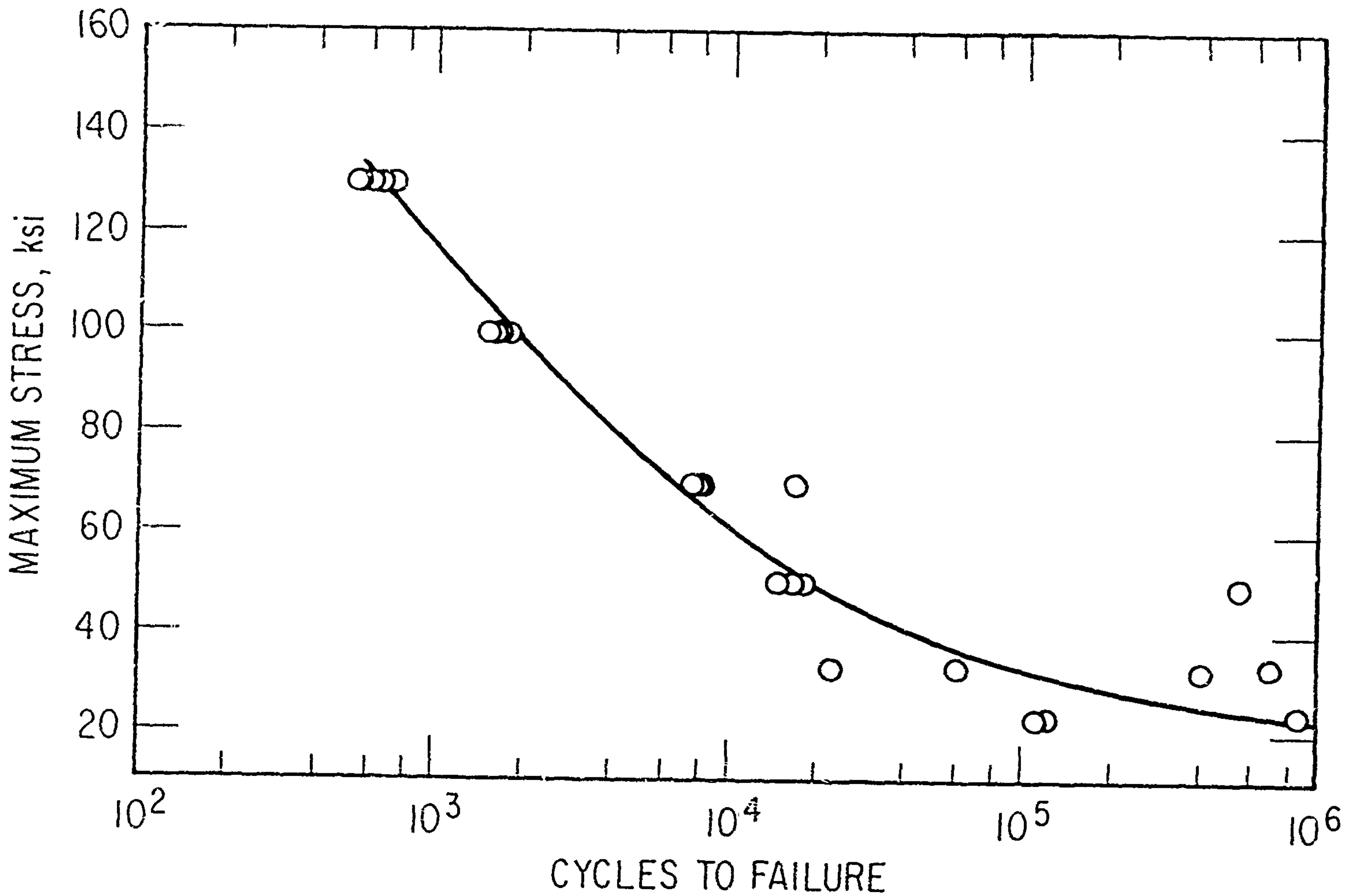


Fig. 16. Notched, S-N Behavior of Annealed Forgings Tested in the Longitudinal Direction ($K_T = 3$, $R = 0.1$, Material No. 11, Ref. 4)

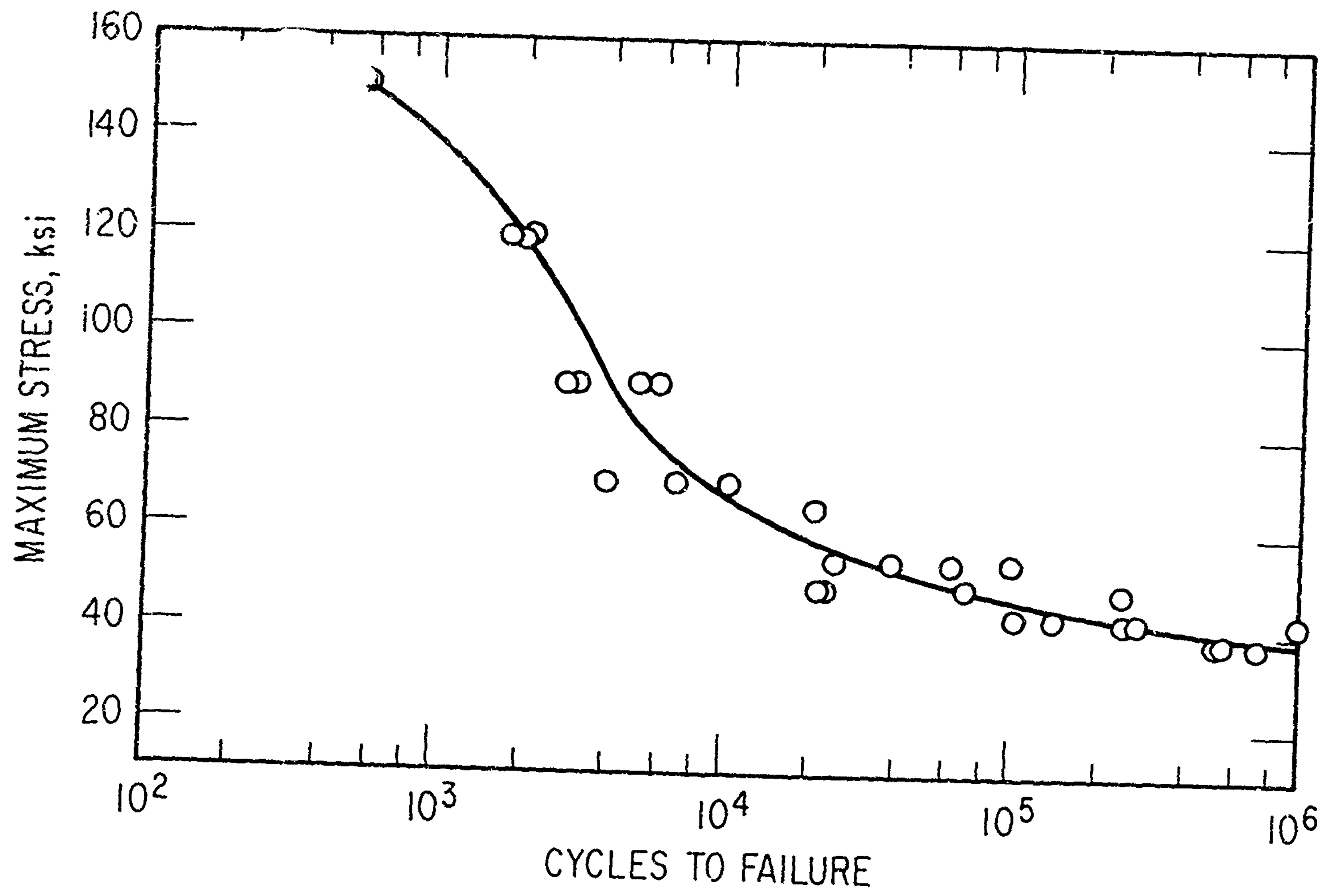


Fig. 17. Notched, S-N Behavior of Annealed Forgings Tested in the Transverse Direction (K_T = 3, R = 0.1, Material No. 11, Ref. 4)

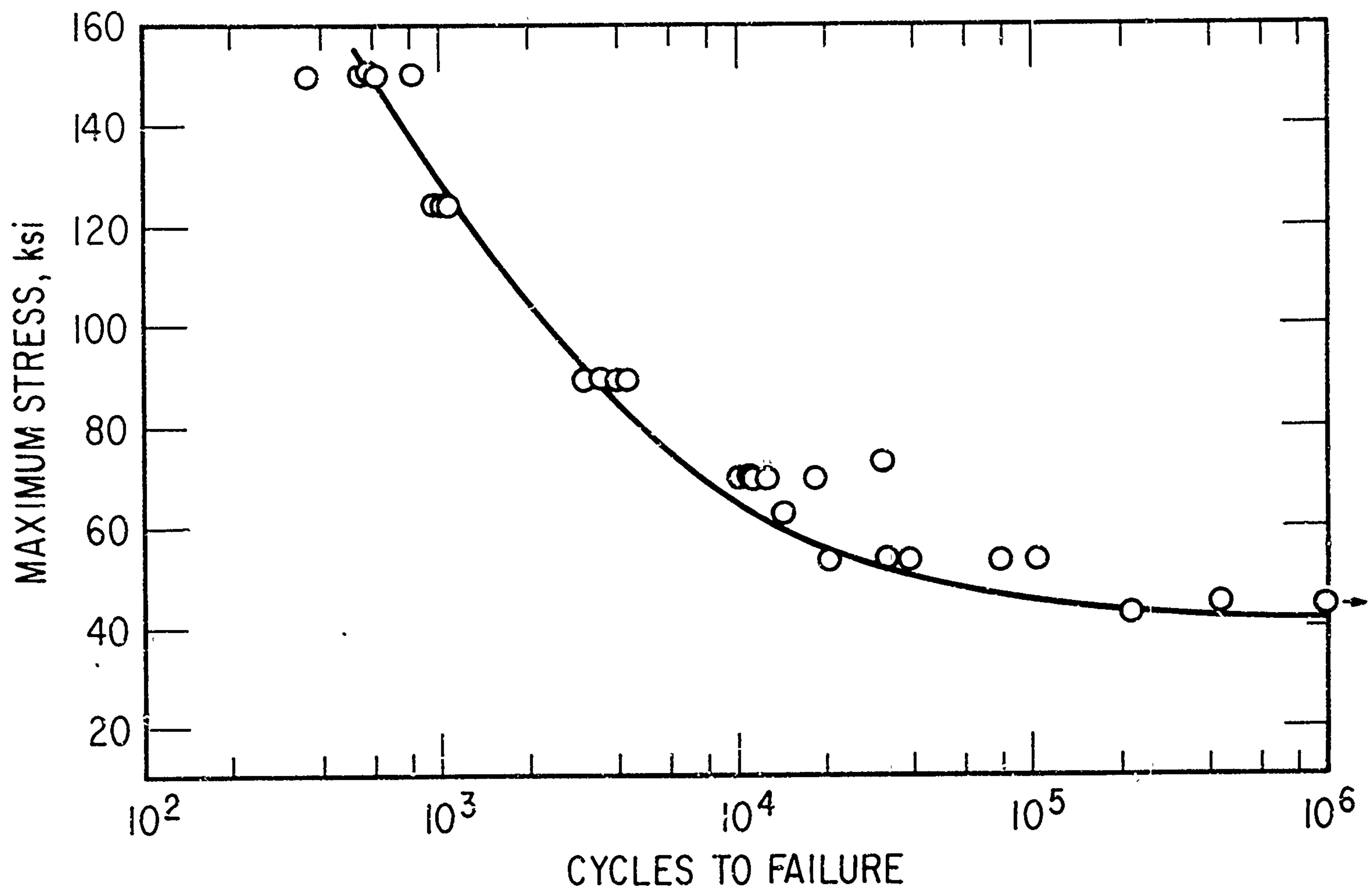


Fig. 18. Notched, S-N Behavior of Annealed Forgings Tested in the Short Transverse Direction ($K_T = 3$, $R = 0.1$, Material No. 11, Ref. 4)

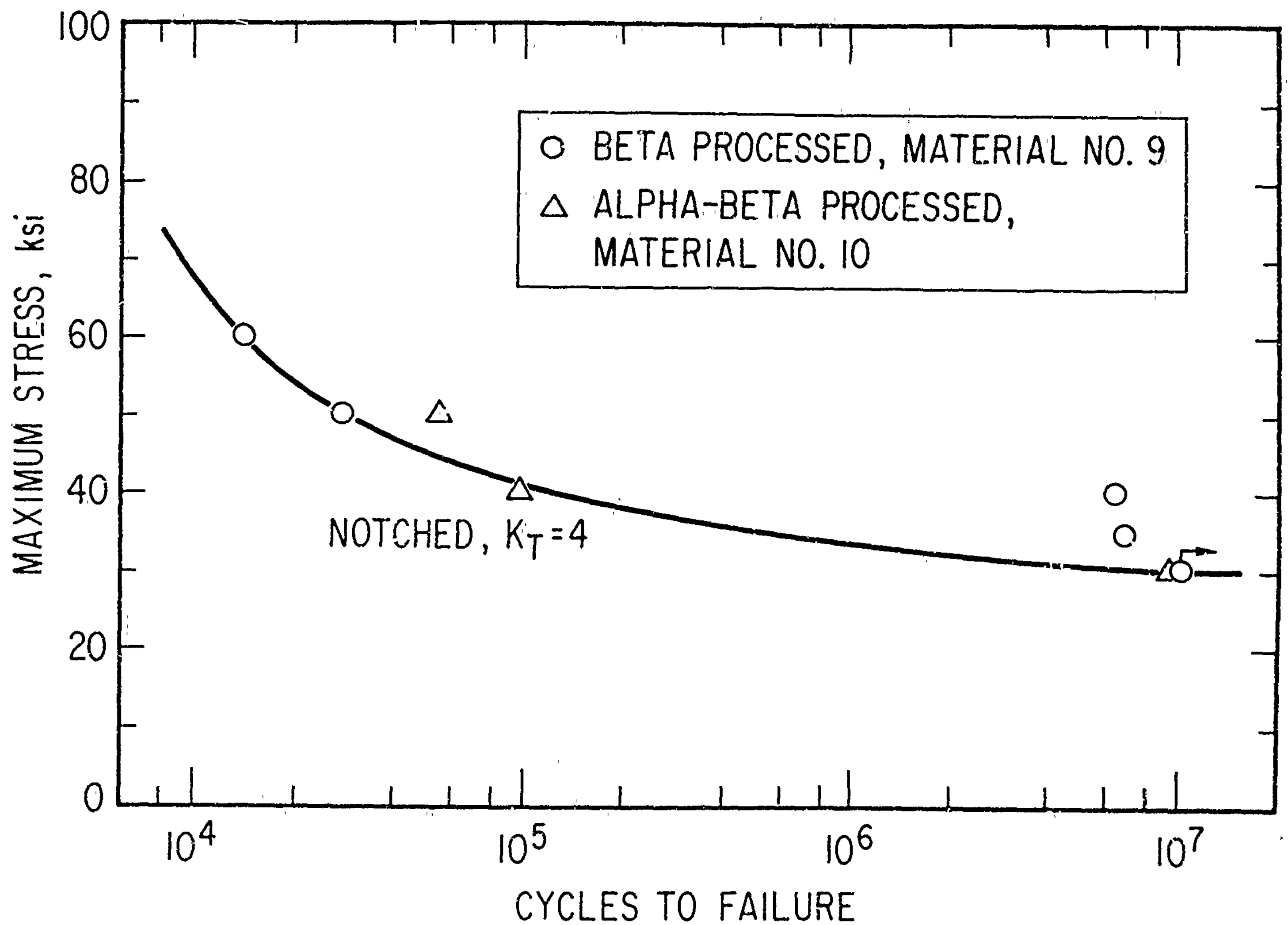


Fig. 19. Notched, S-N Behavior of Annealed Forgings Processed in the Alpha and Alpha-Beta Fields (R = 0.1, Ref. 16)

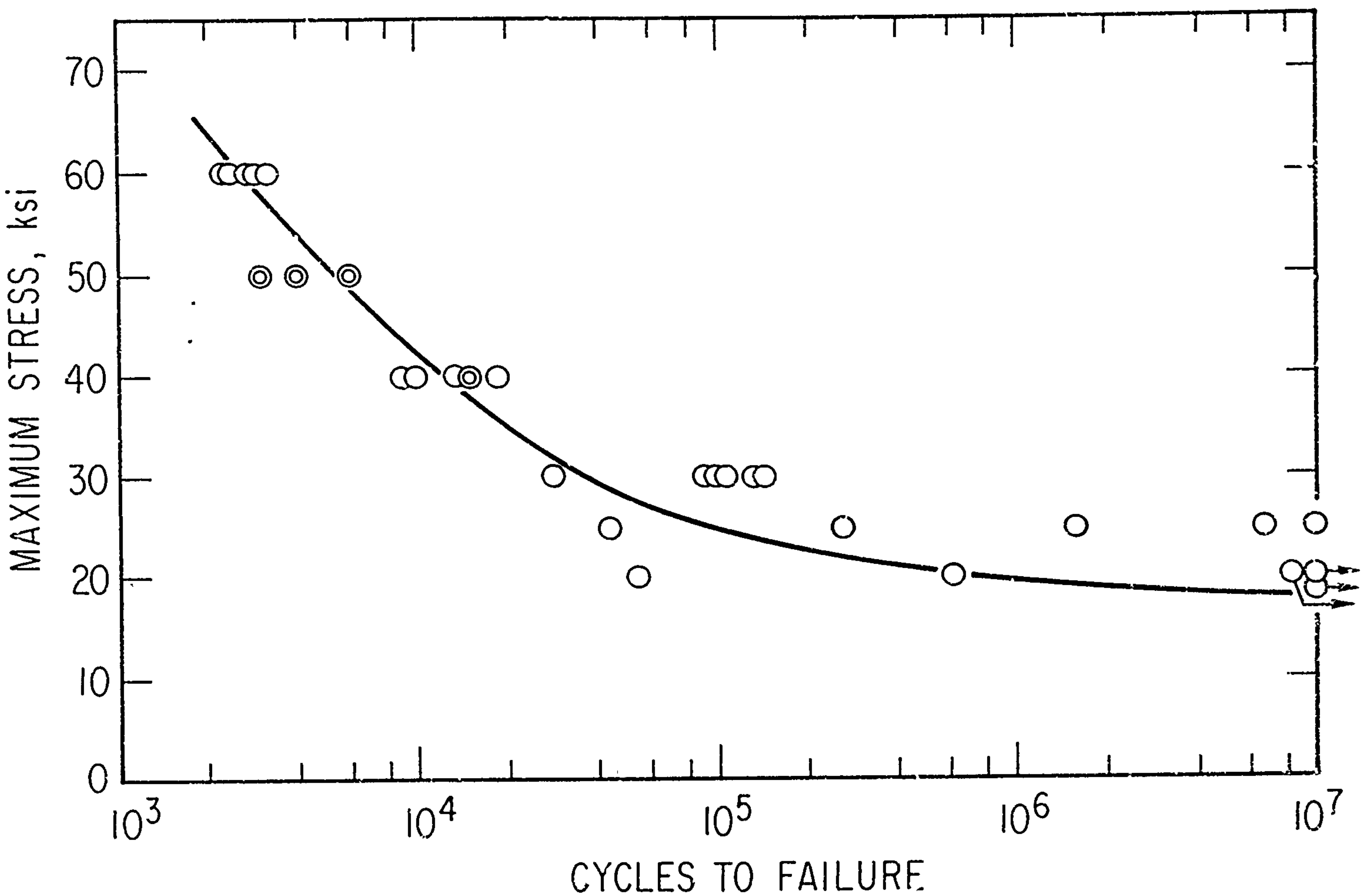


Fig. 20. Notched, S-N Behavior of Annealed Forgings Tested in the Longitudinal Direction ($K_T = 5$, $R = -1$, Material No. 11, Ref. 4)

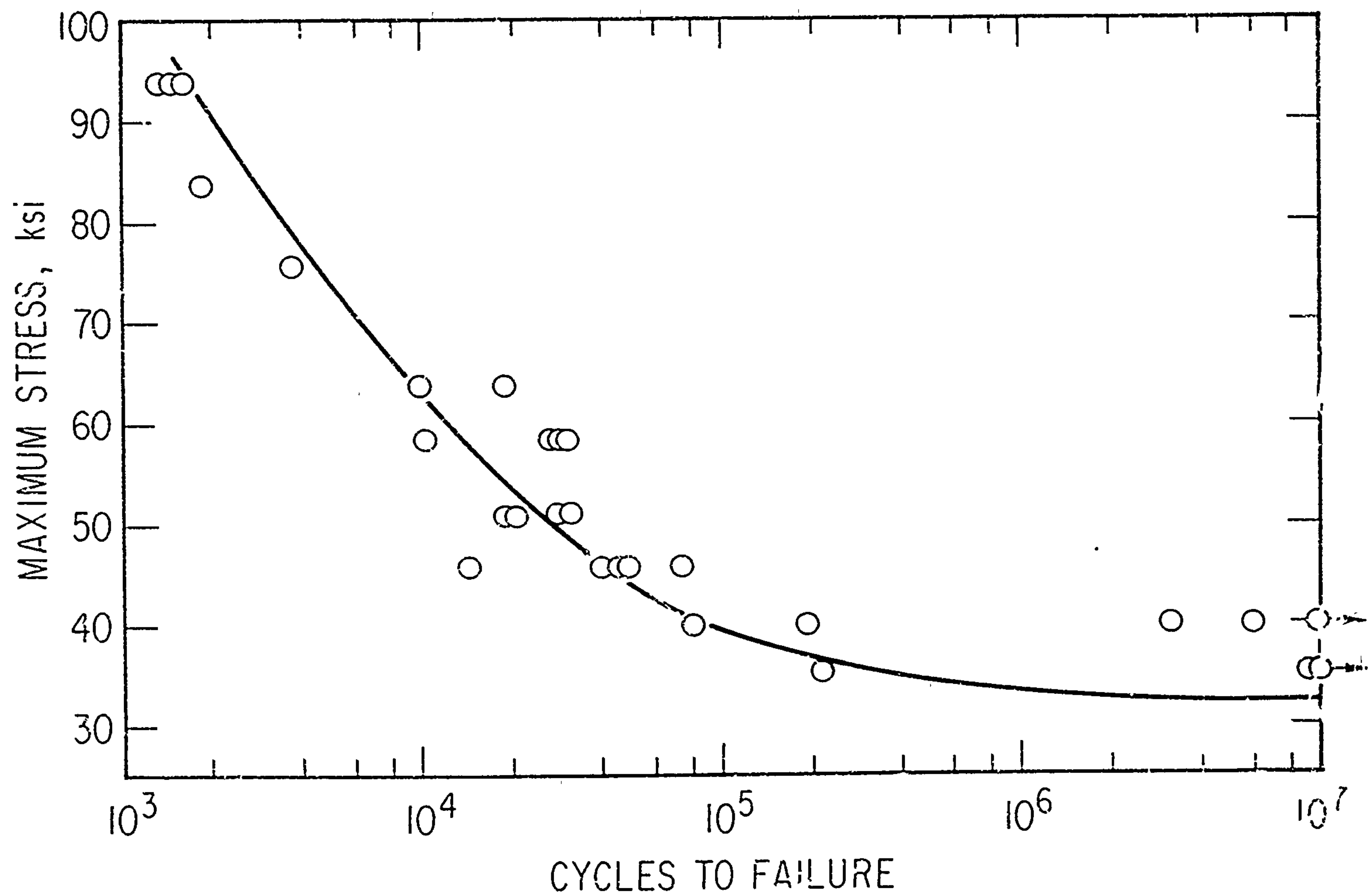


Fig. 21. Notched, S-N Behavior of Annealed Forgings Tested in the Longitudinal Direction (K_T = 5, R = 0.1, Material No. 11, Ref. 4)

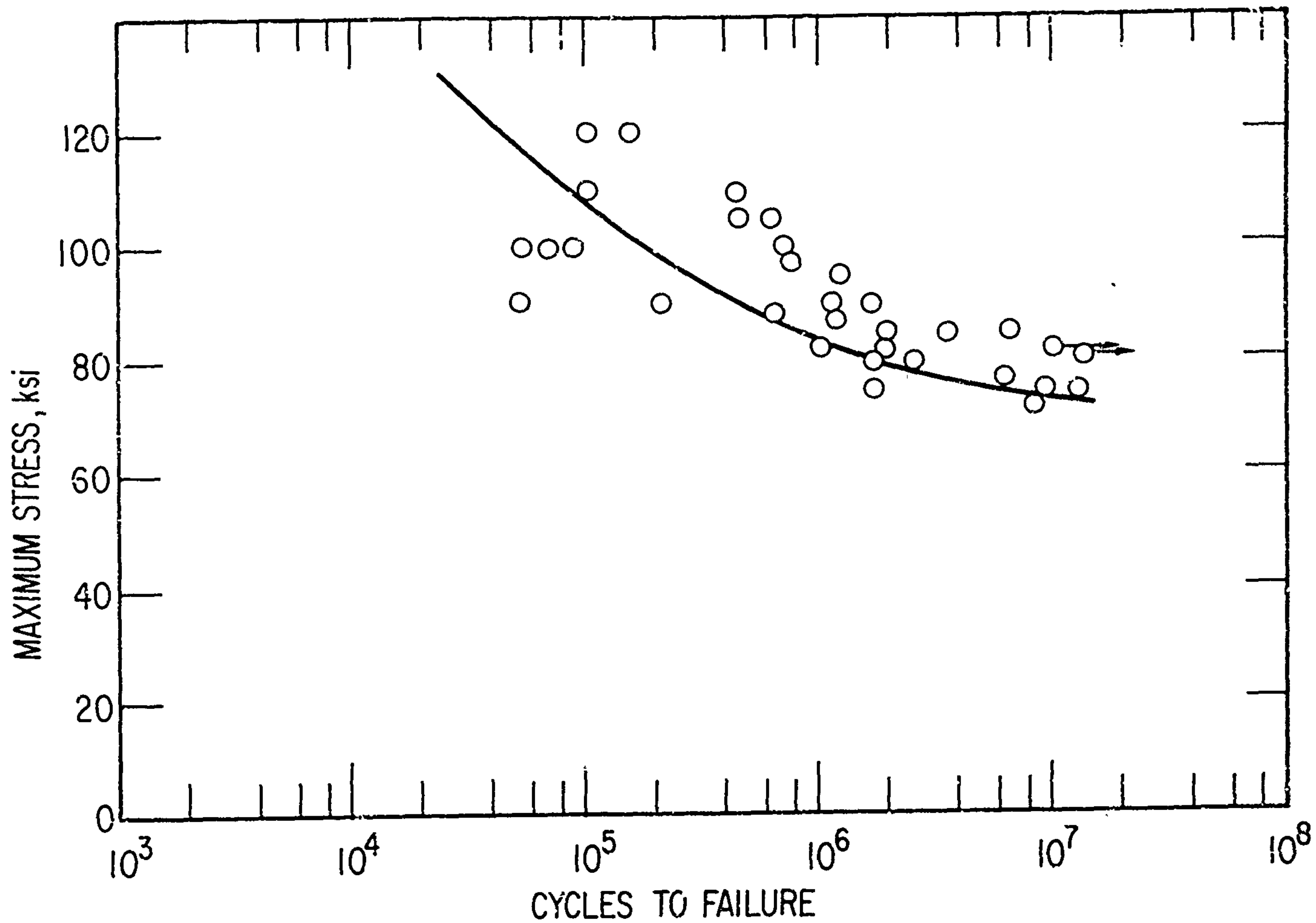


Fig. 22. Unnotched, S-N Behavior of Annealed Extrusions (R =0.01, Material No. 12, Ref. 22)

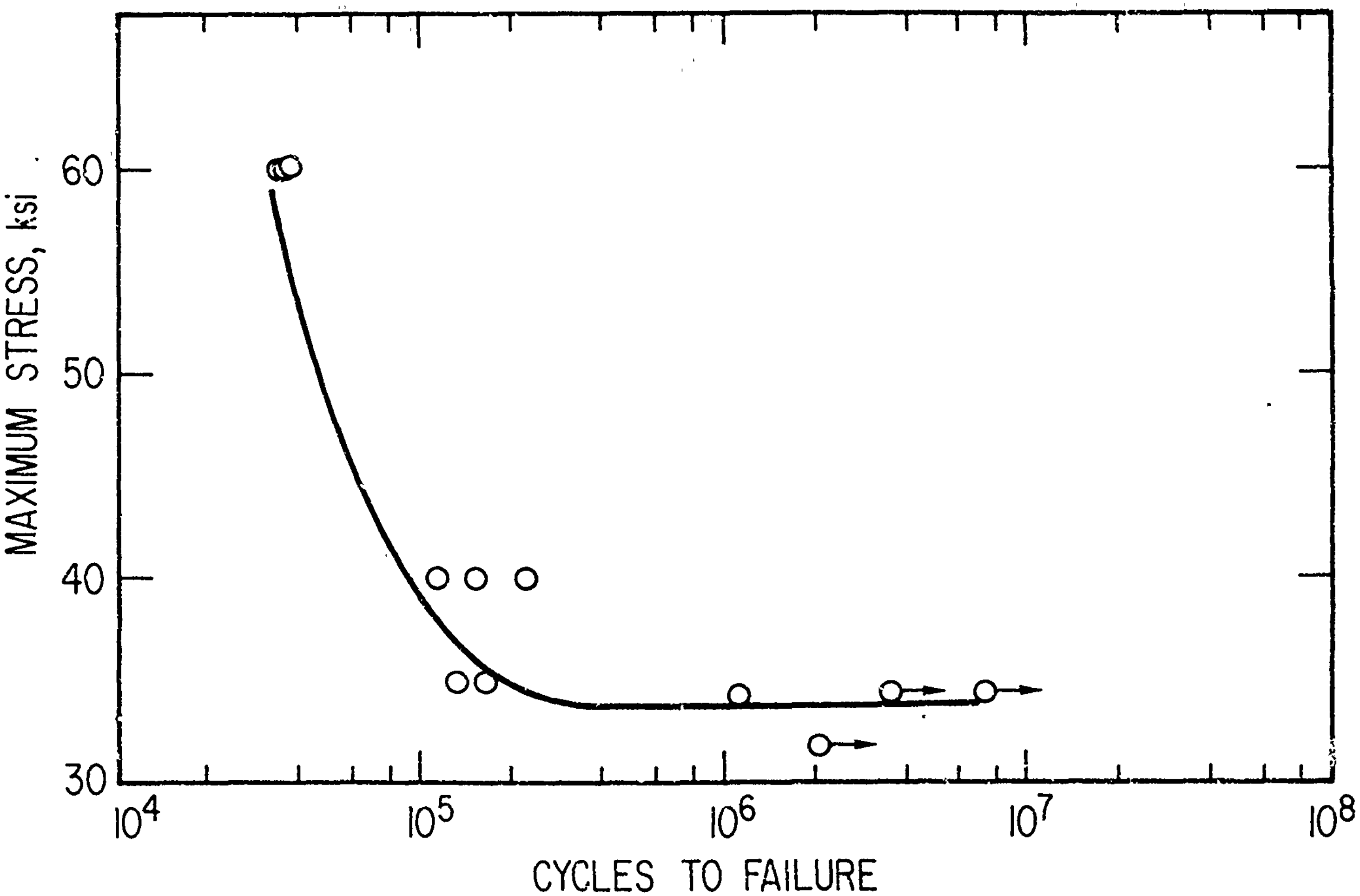


Fig. 23. Notched, S-N Behavior of Annealed Extrusions (R = 0.06, Material No. 13, Ref. 19)

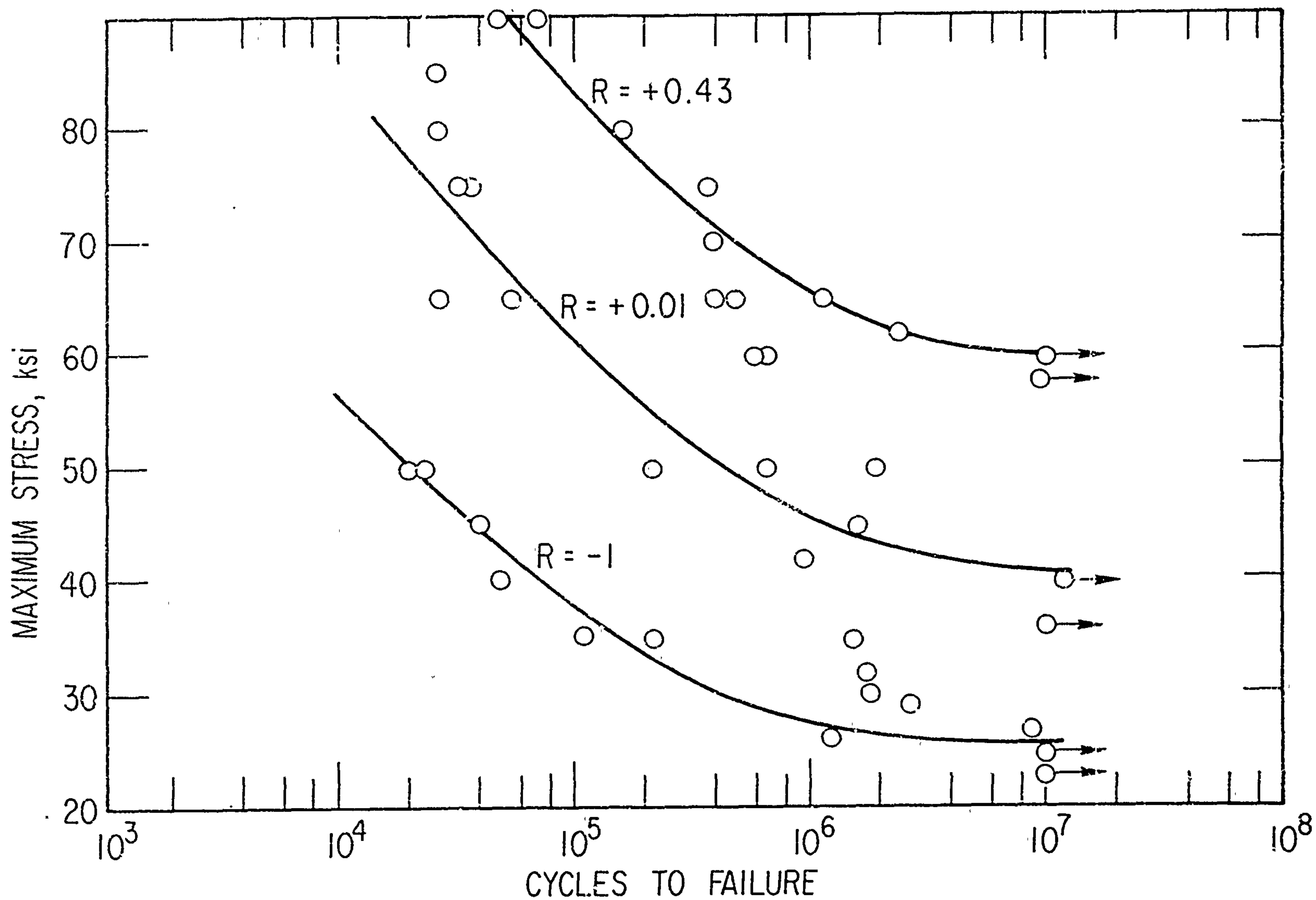


Fig. 24. Notched, S-N Behavior of Annealed Extrusions (K_T = 2.76, Material No. 12, Ref. 22)

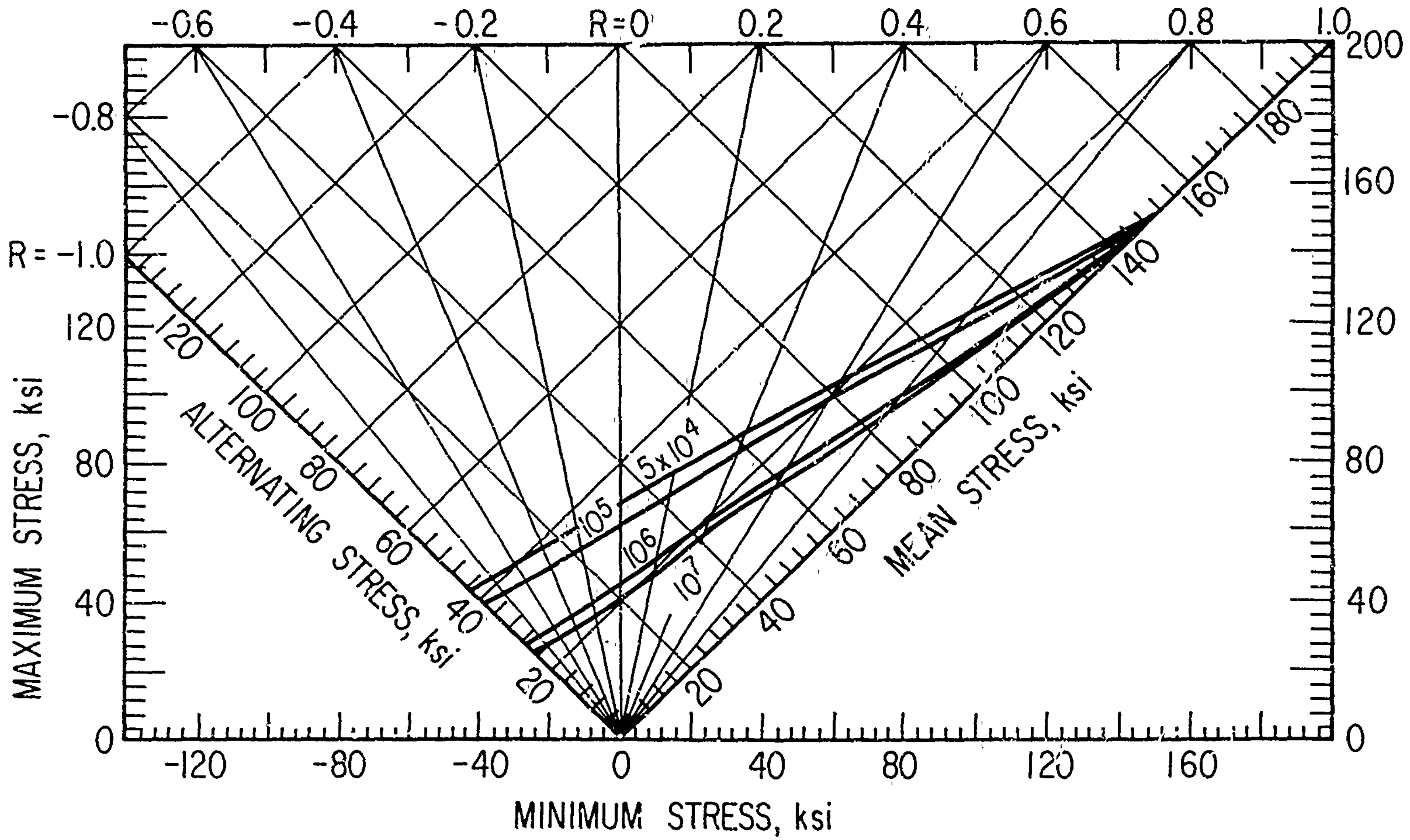


Fig. 25. Master Diagram of Notched, Annealed Extrusions (K_T = 2.76, Material No. 12, Ref. 22)

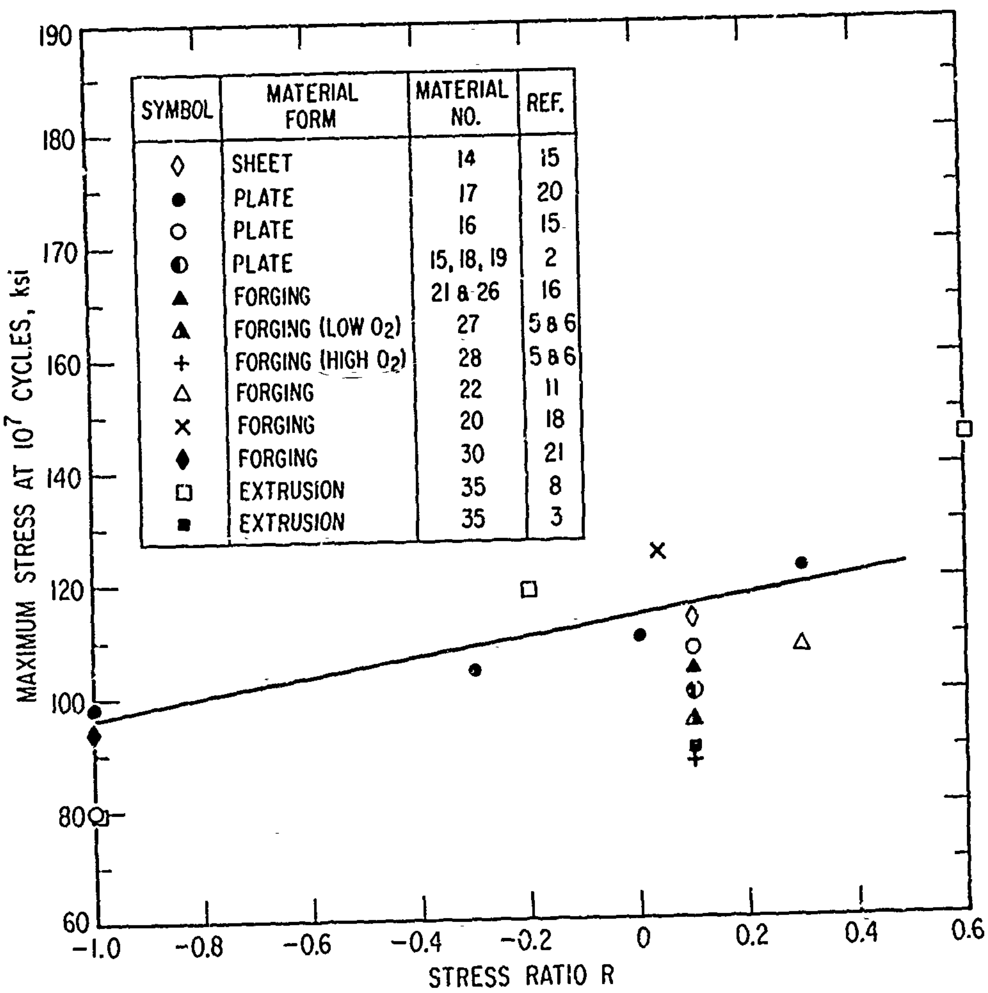


Fig. 26. Unnotched, Fatigue Strength of Ti-6Al-6V-2Sn in the STA Condition

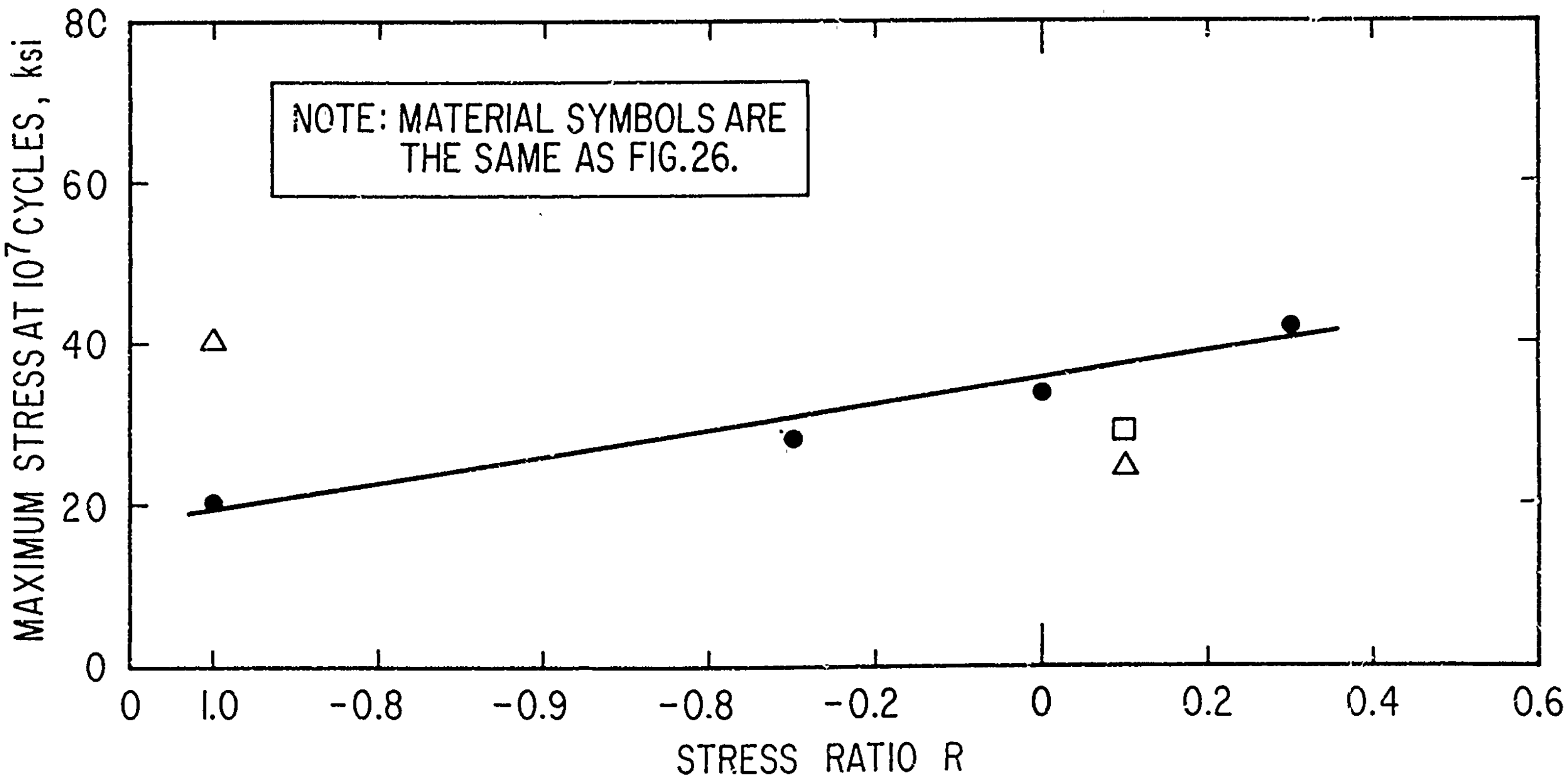


Fig. 27. Notched, Fatigue Strength of Ti-6Al-6V-2Sn in the STA Condition (K_T = 3)

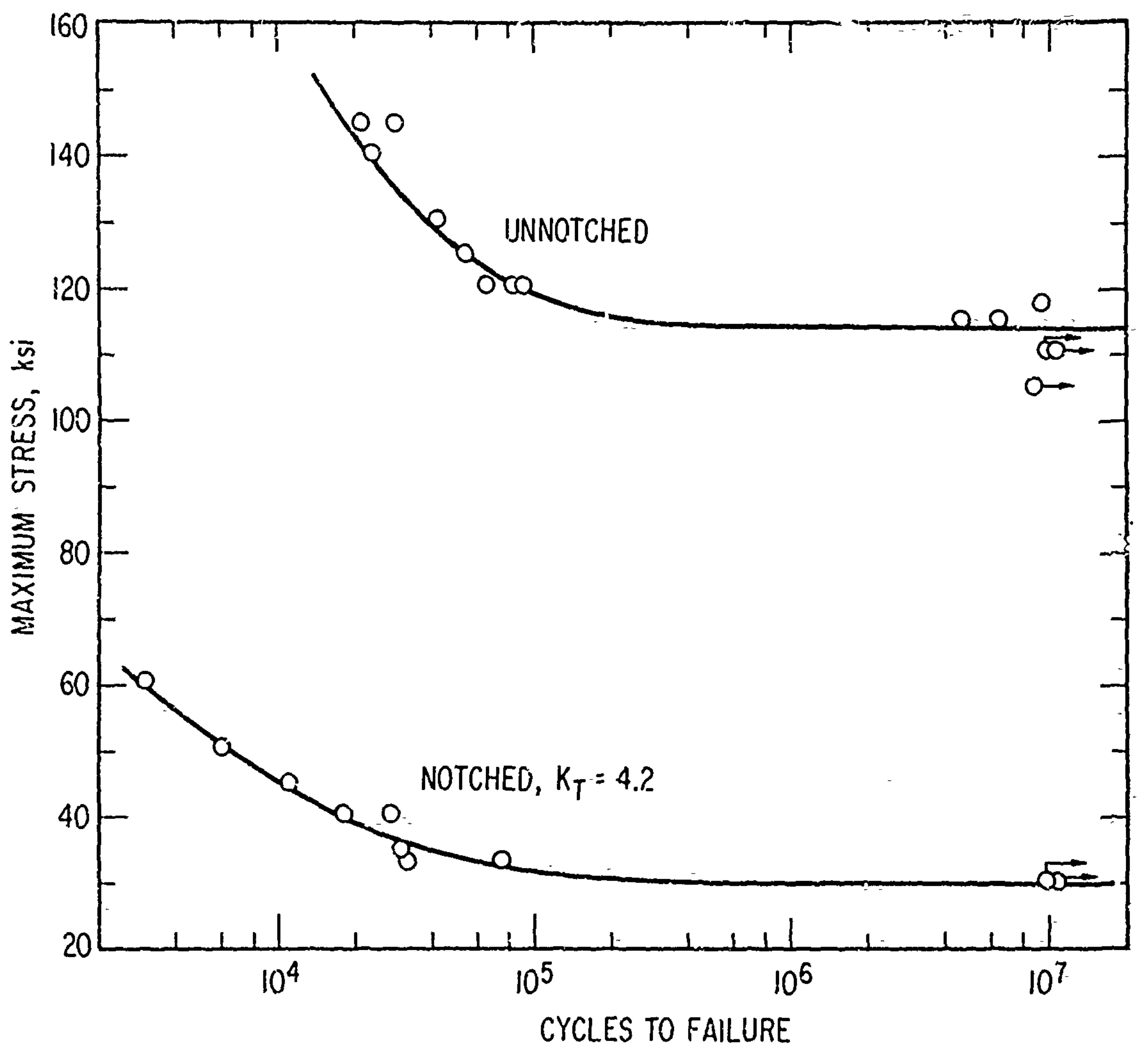


Fig. 28. Unnotched and Notched, S-N Behavior of STA Sheet (R = 0.1, Material No. 14, Ref. 15)

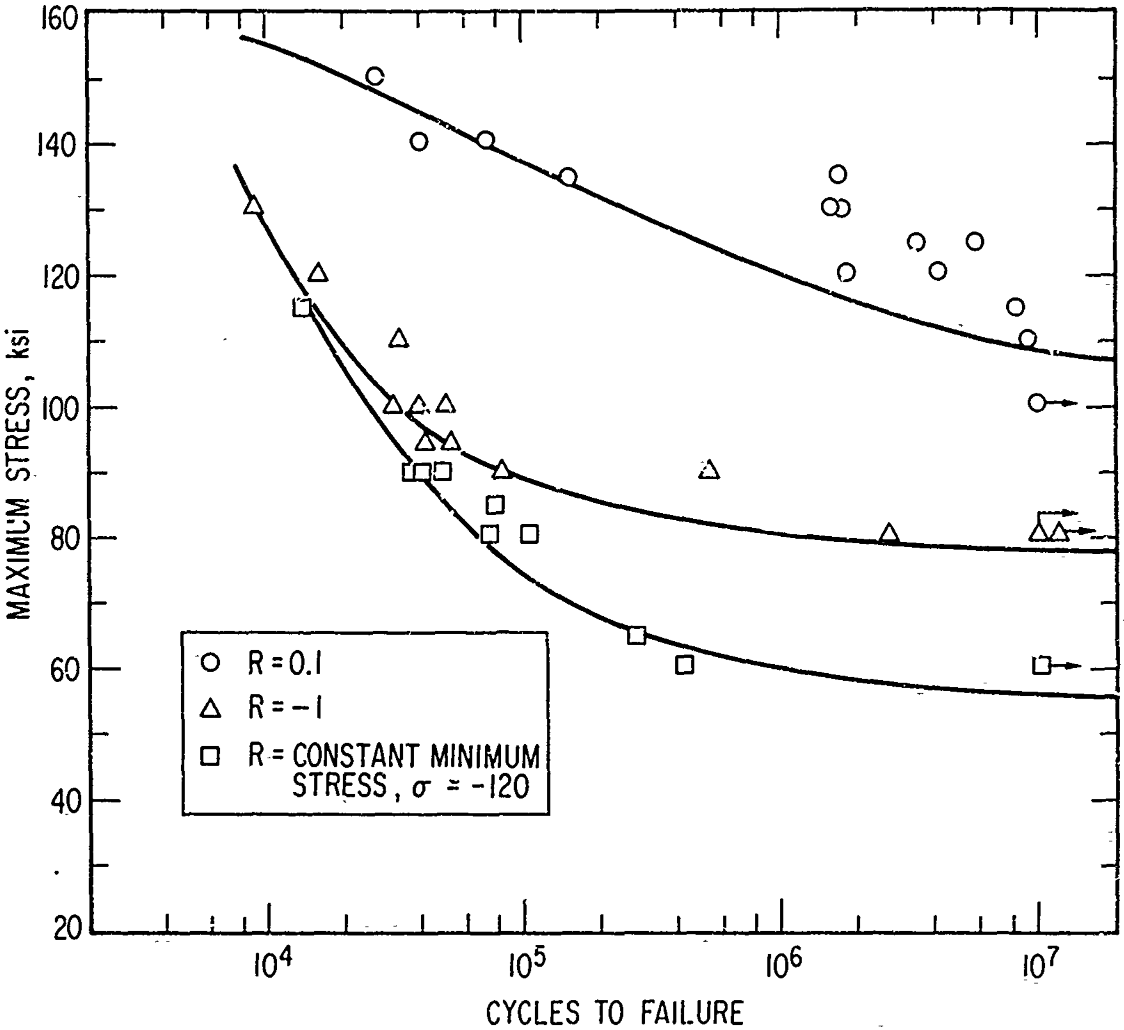


Fig. 29. Unnotched, S-N Behavior of STA Plate (Material No. 16, Ref. 15)

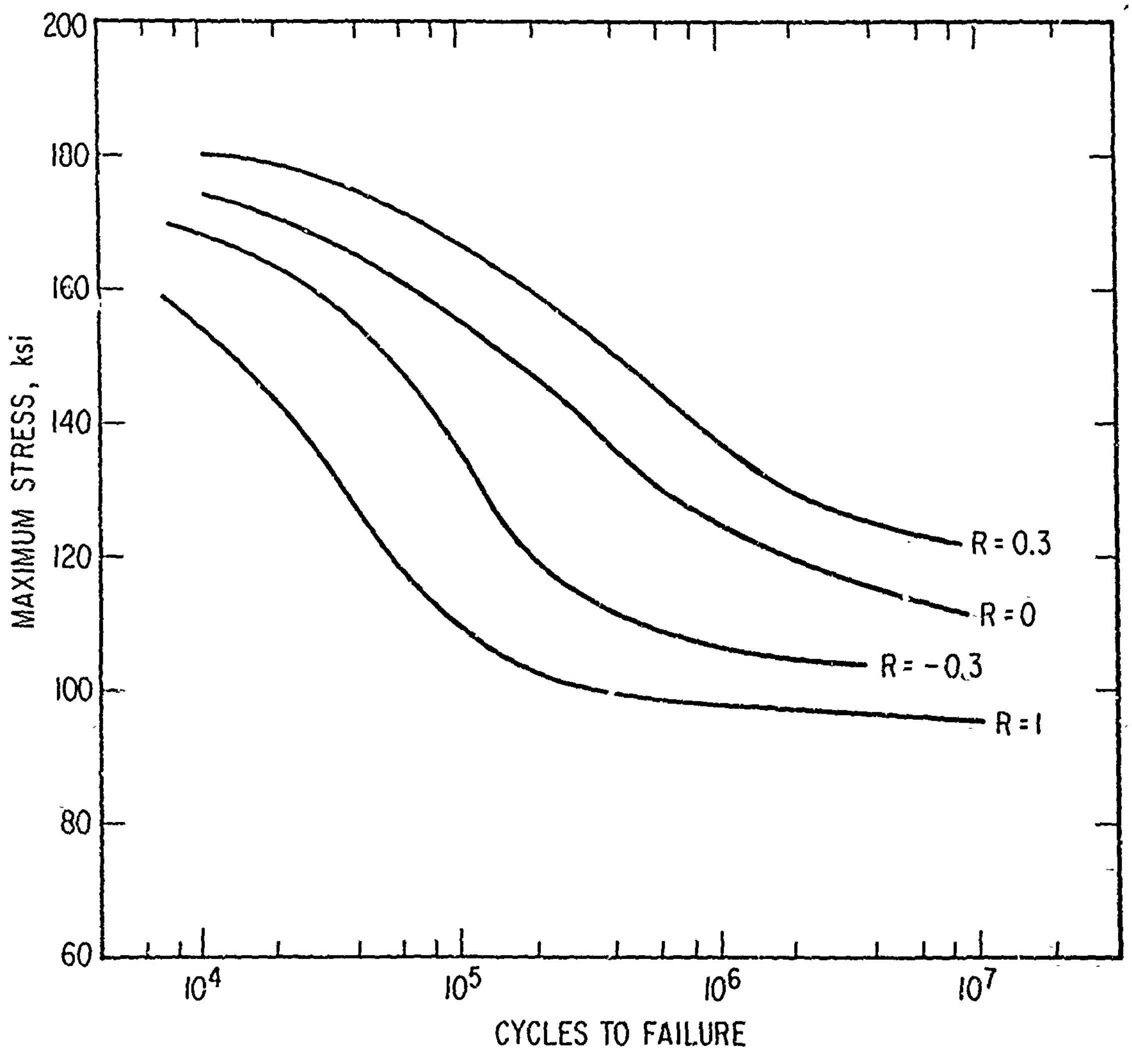


Fig. 30. Unnotched, S-N Behavior of STA Plate (Material No. 17, Ref. 20)

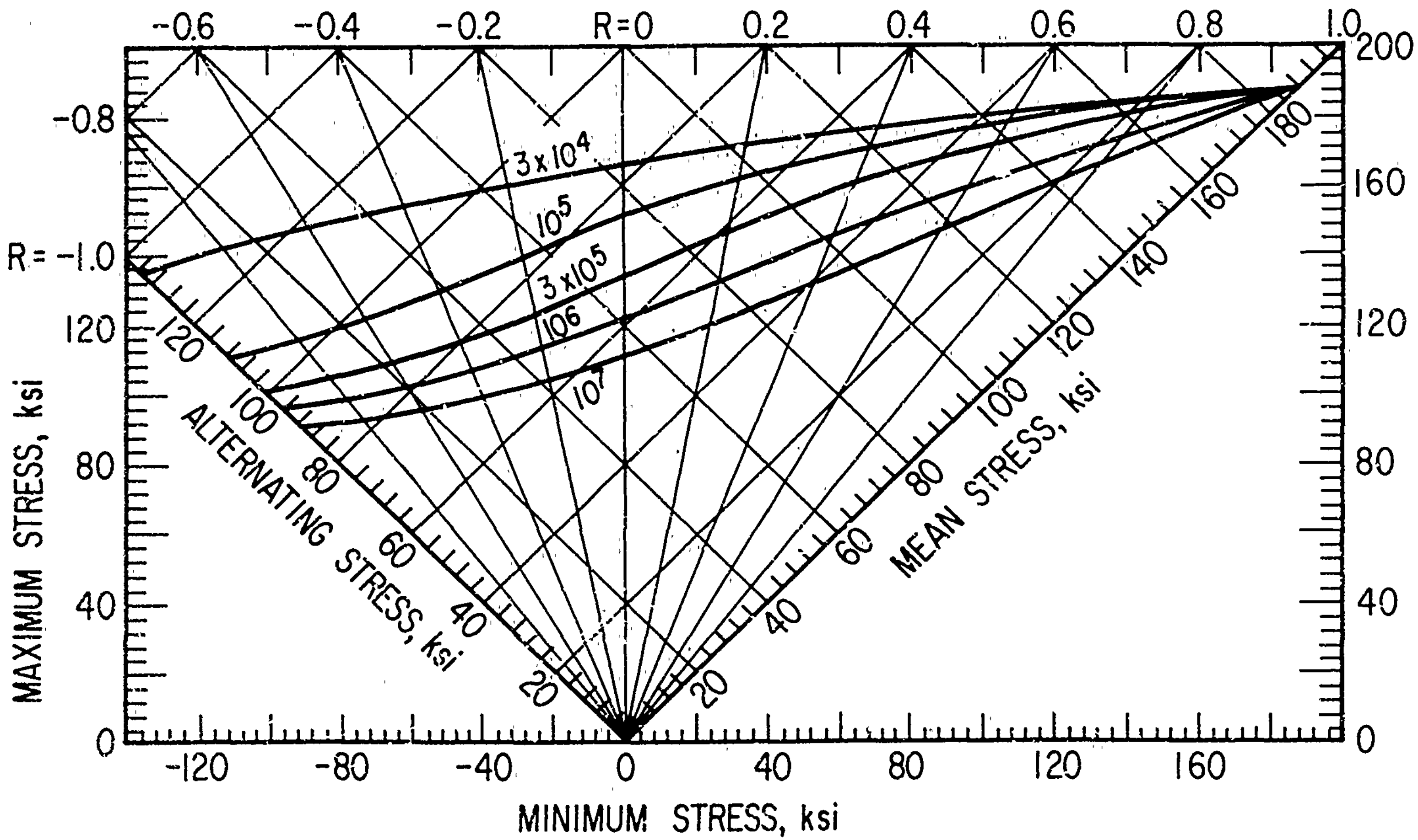


Fig. 31. Master Diagram of Unnotched, STA Plate (Material No. 17, Ref. 20)

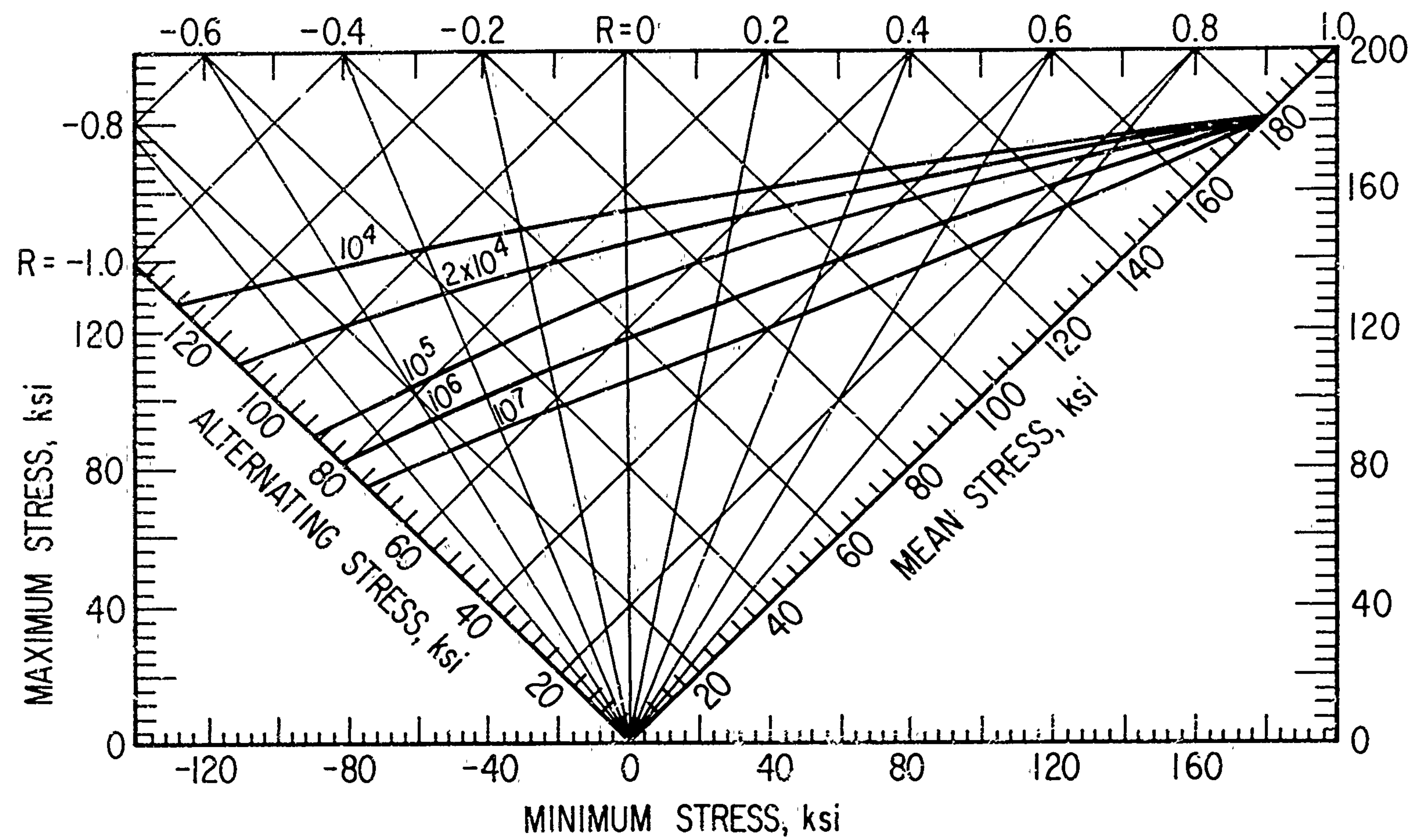


Fig. 32. Master Diagram of Unnotched, STA Plate (Material No. 16, Ref. 15)

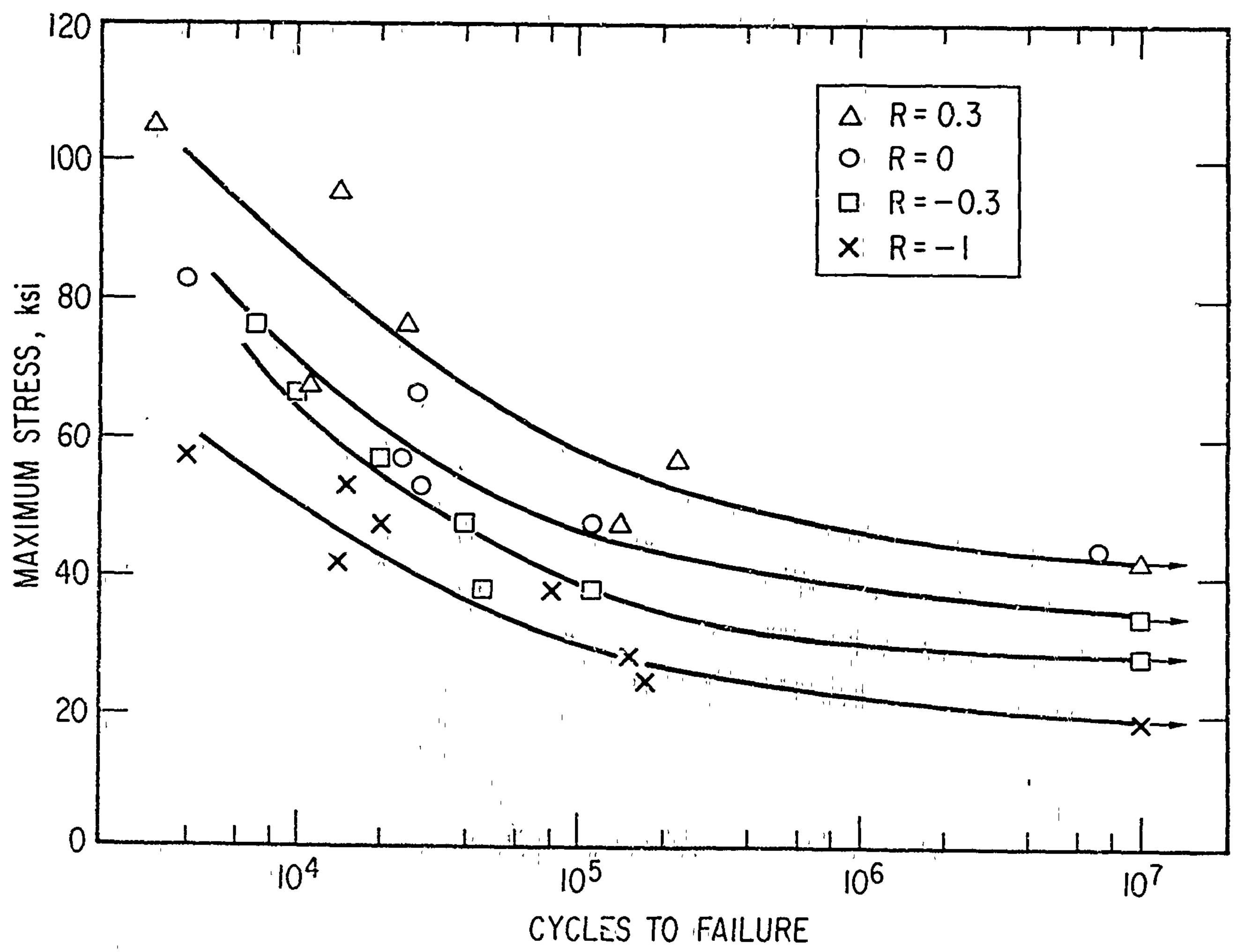


Fig. 33. Notched, S-N Behavior of STA Plate (K_T = 3, Material No. 17, Ref. 20)

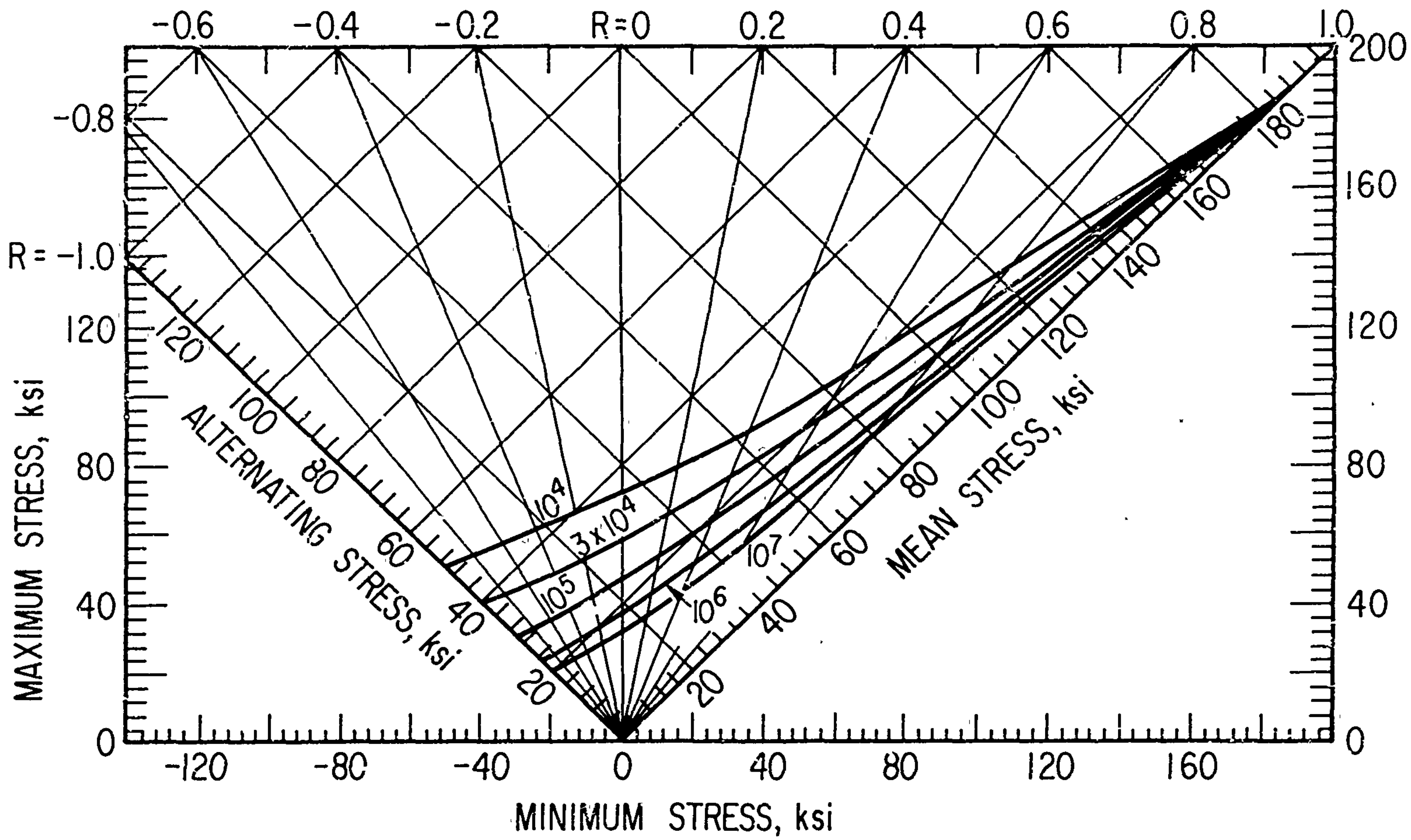


Fig. 34. Master Diagram of Notched, STA Plate (K_T = 3, Material No. 17, Ref. 20)

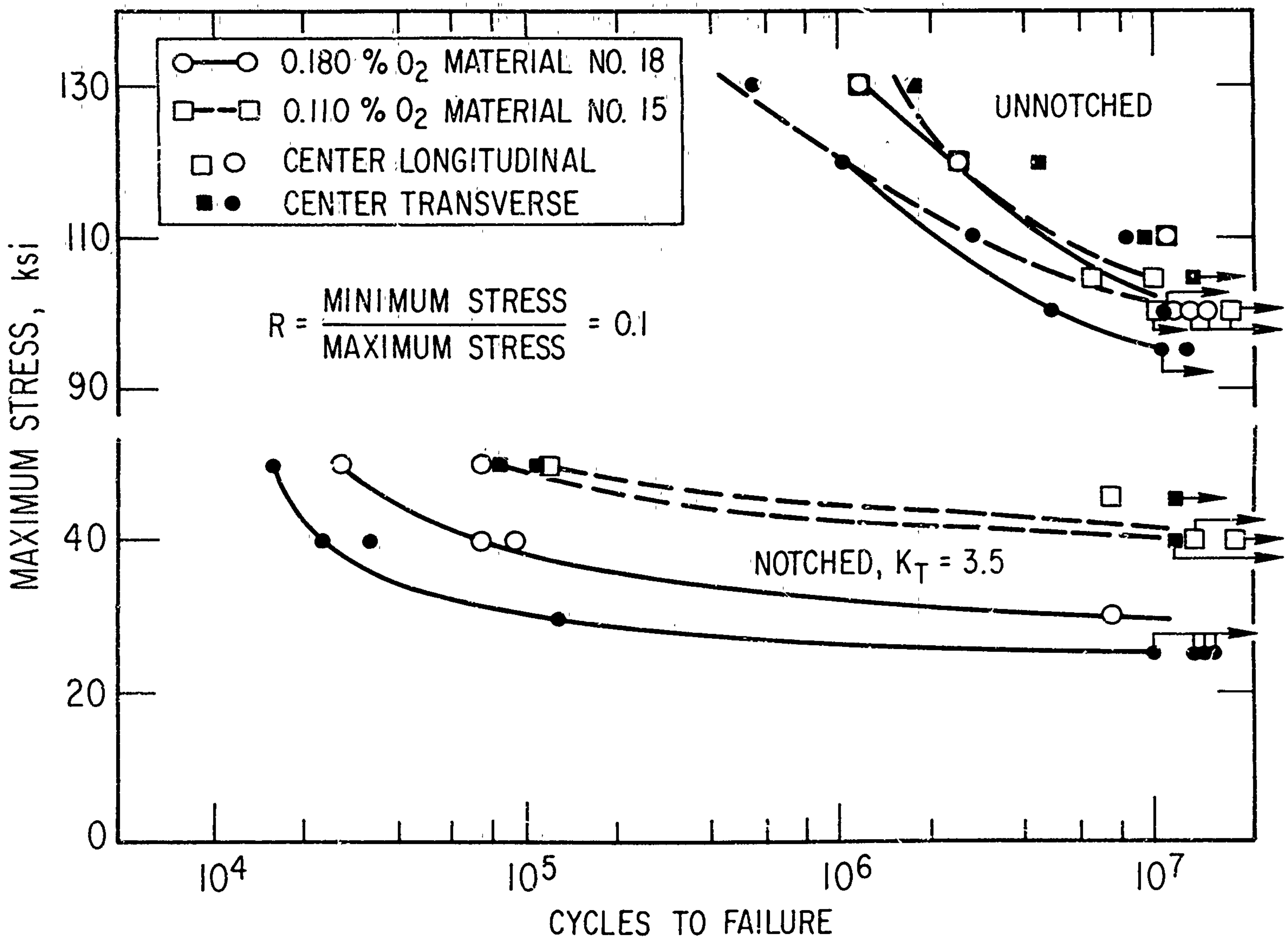


Fig. 35. Notched and Unnotched, S-N Curves for STA Plates of Different Oxygen Levels (Refs. 1 and 2)

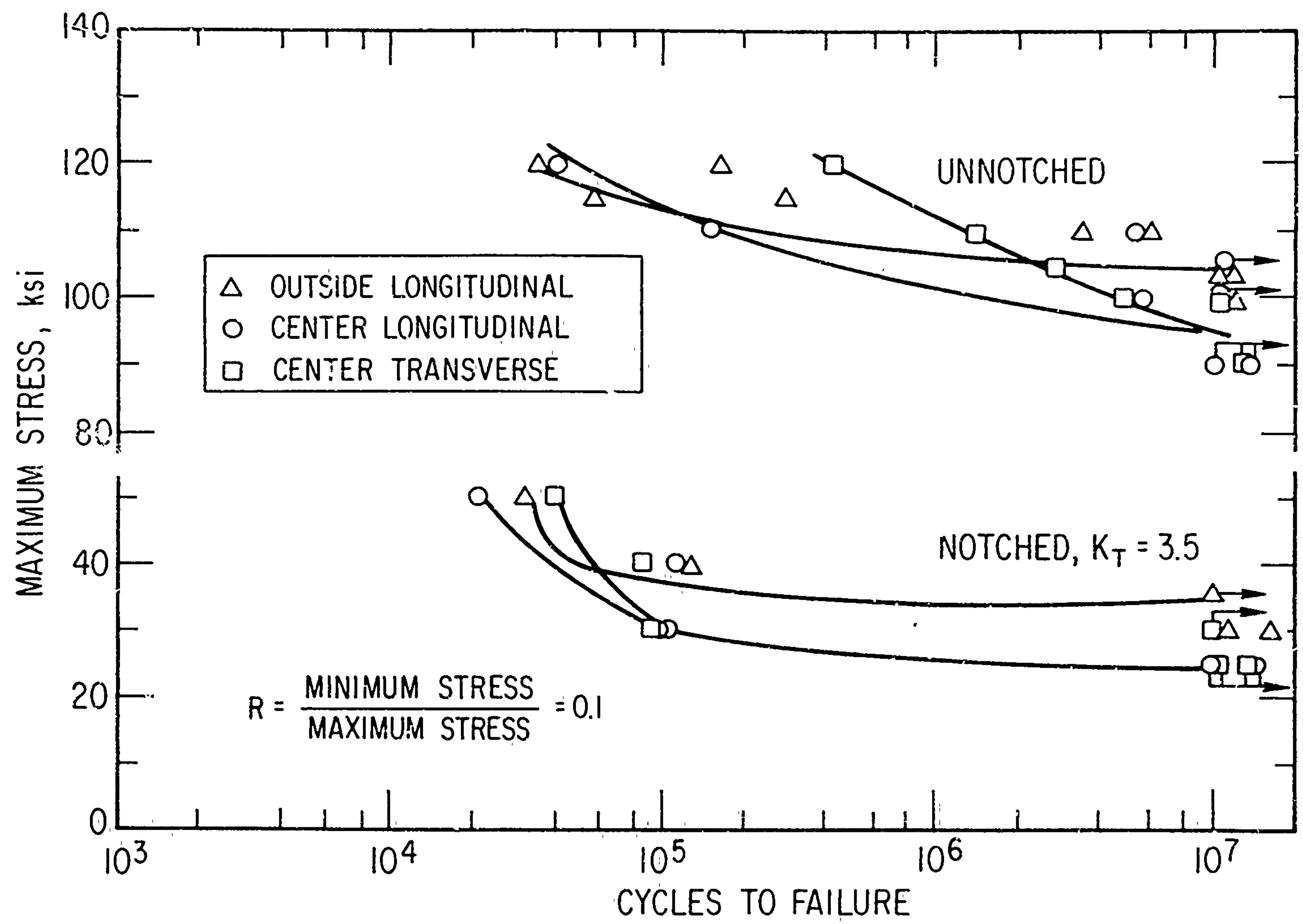


Fig. 36. Notched and Unnotched, S-N Behavior of STA, 2-in. Plate (Material No. 19, Refs. 1 and 2)

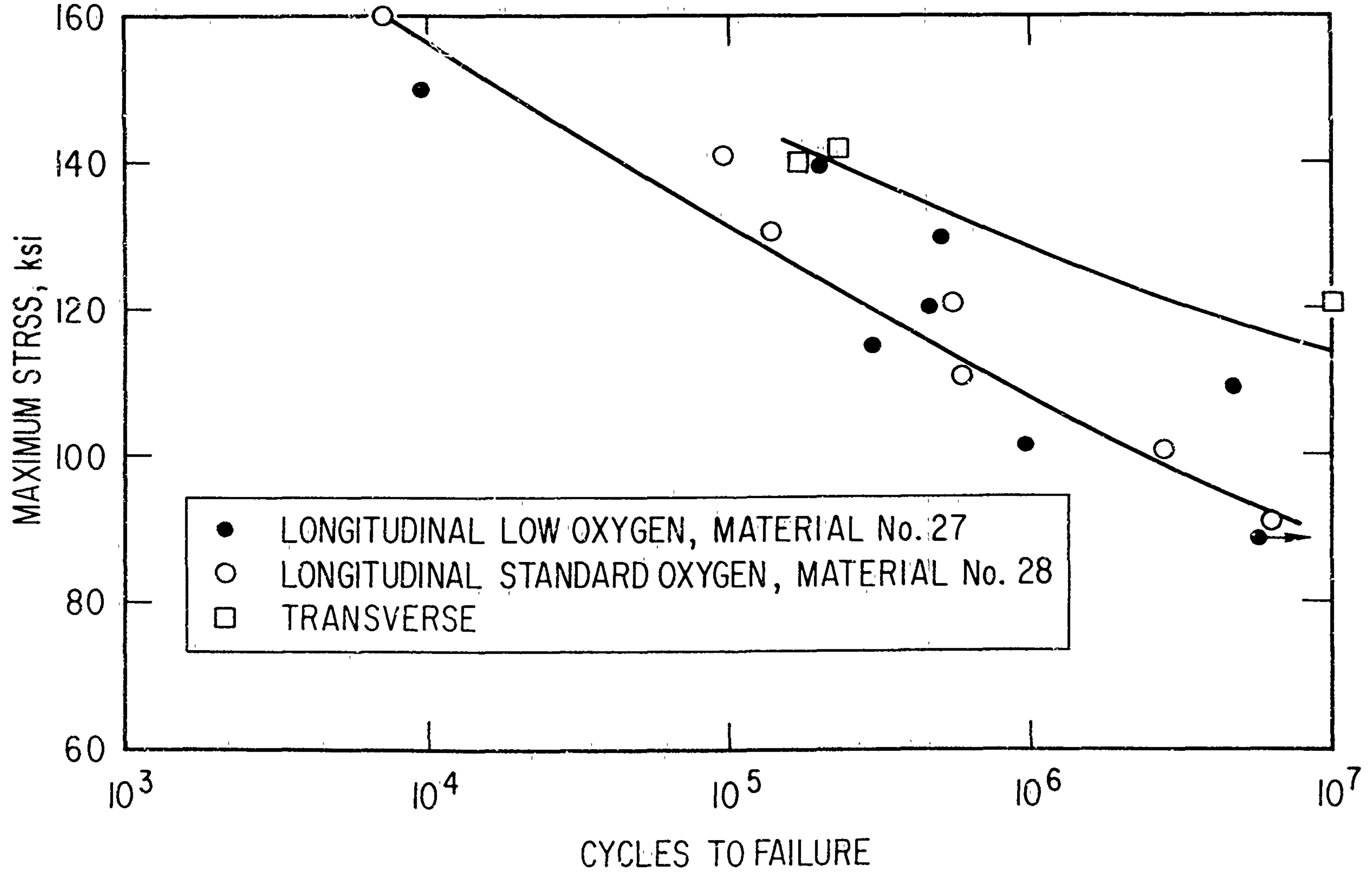


Fig. 37. Unnotched, S-N Behavior of STA Forgings (R = 0.1, Refs. 5 and 6).

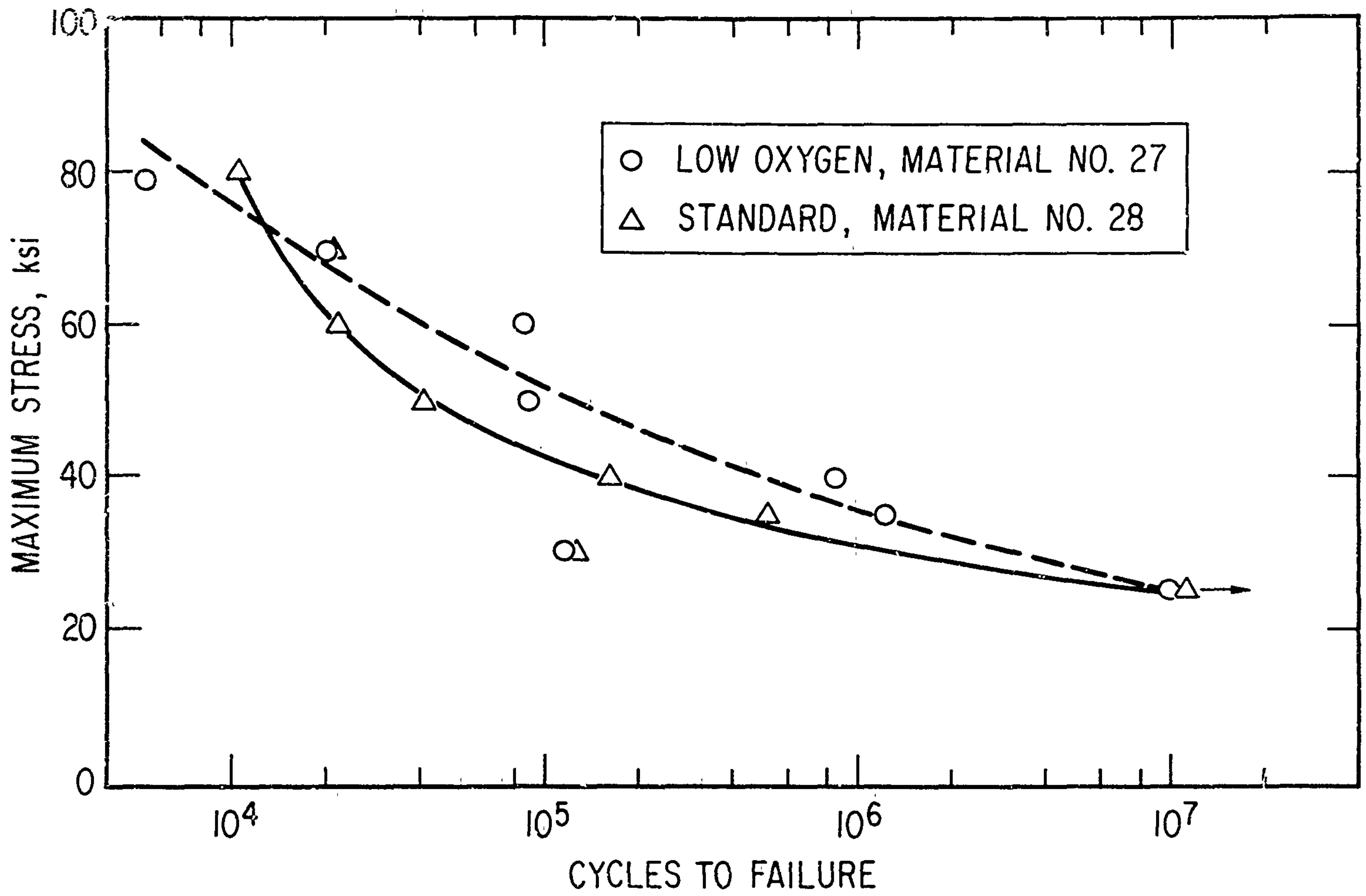


Fig. 38. Notched, S-N Behavior of STA Forgings (K_T = 3, R = 0.1, Refs. 5 and 6).

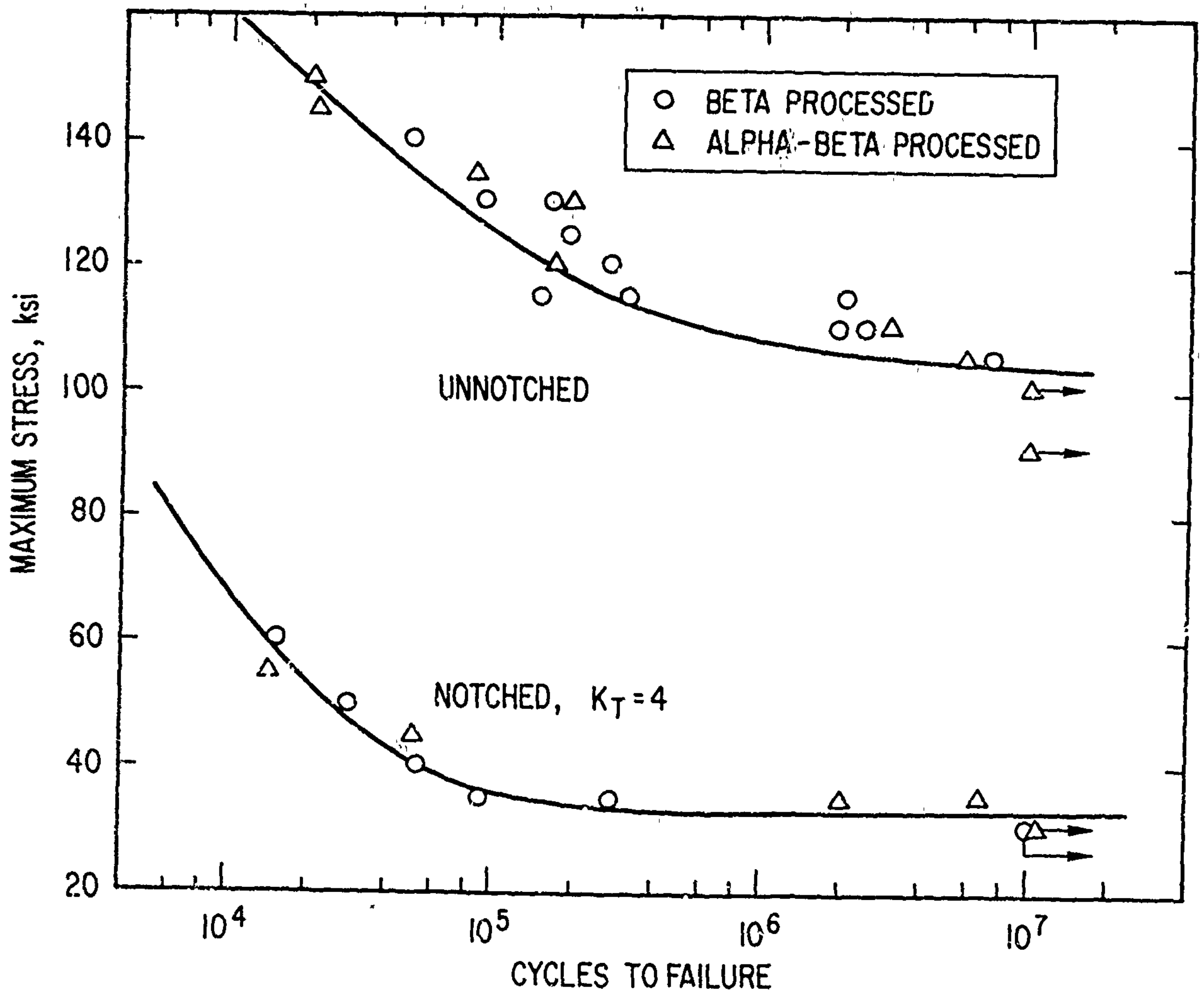


Fig. 39. Notched and Unnotched, S-N Behavior of STA Forgings Processed in the Alpha and Alpha-Beta Fields (R = 0.1, Material No. 26, Ref. 16)

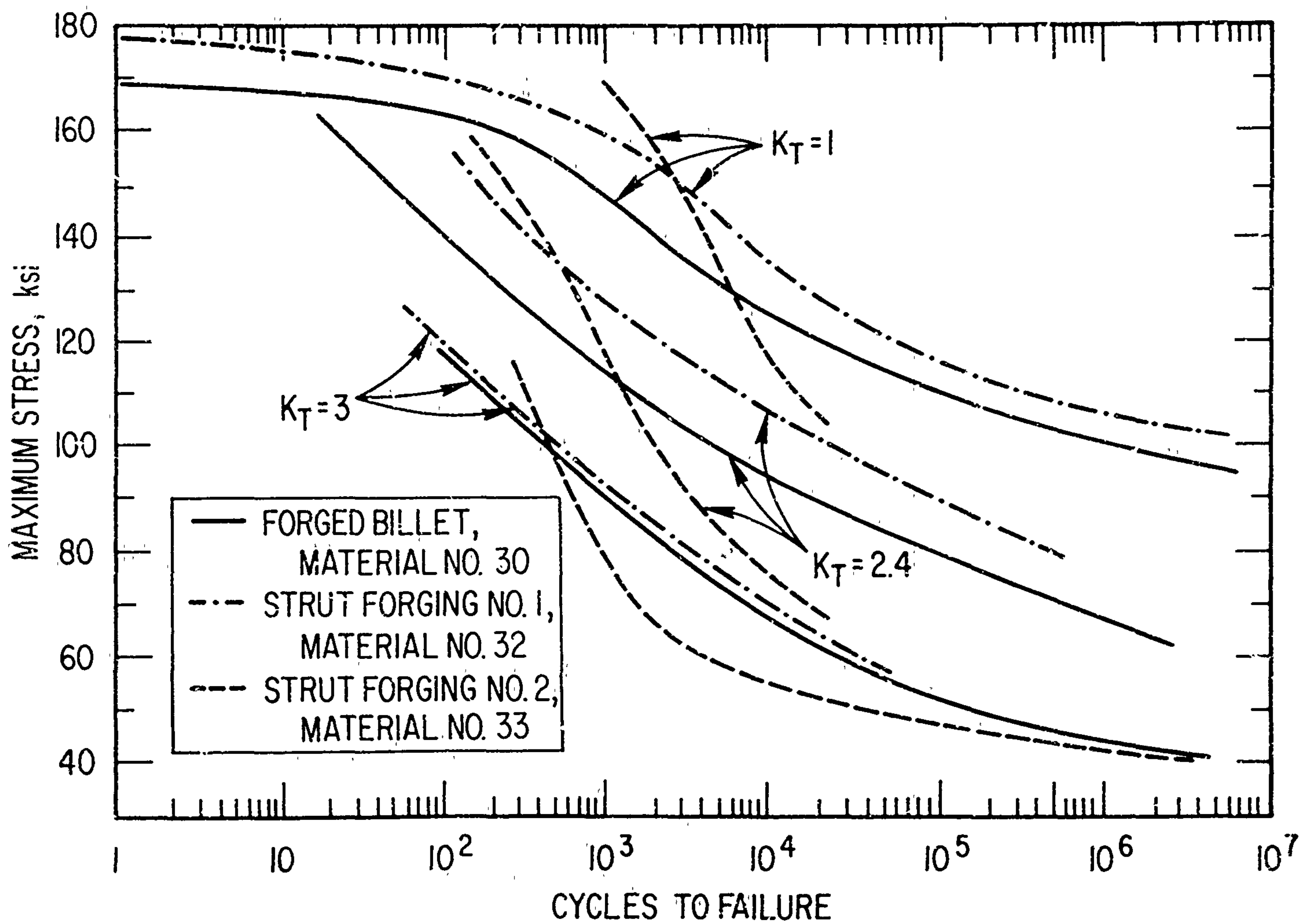


Fig. 40. Notched and Unnotched; S-N Behavior of STA Billet and Component Forgings (R = -1, Ref. 20)

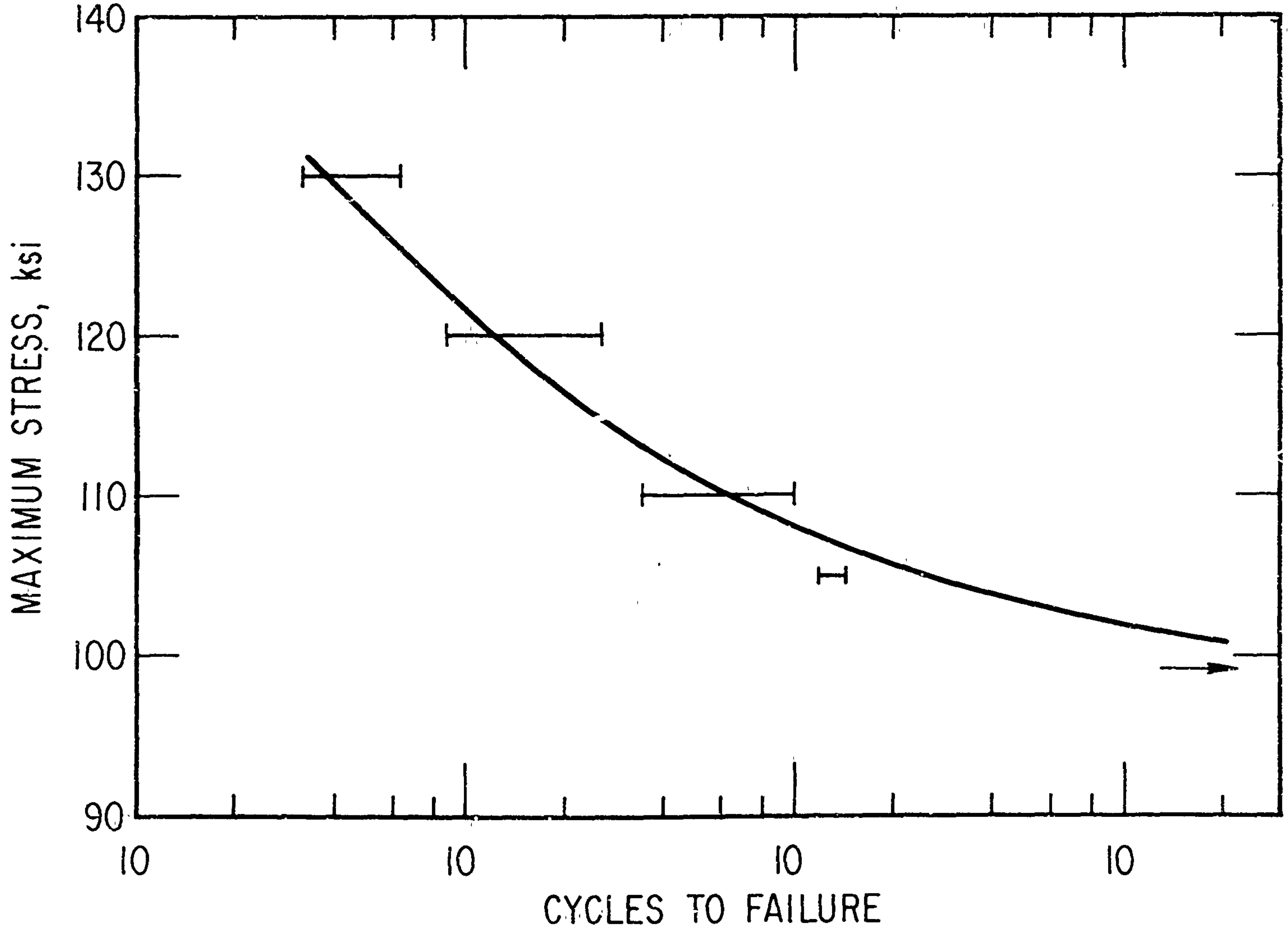


Fig. 41. Unnotched, S-N Behavior of STA Forging (R = 0.3, Material No. 25, Ref. 11)

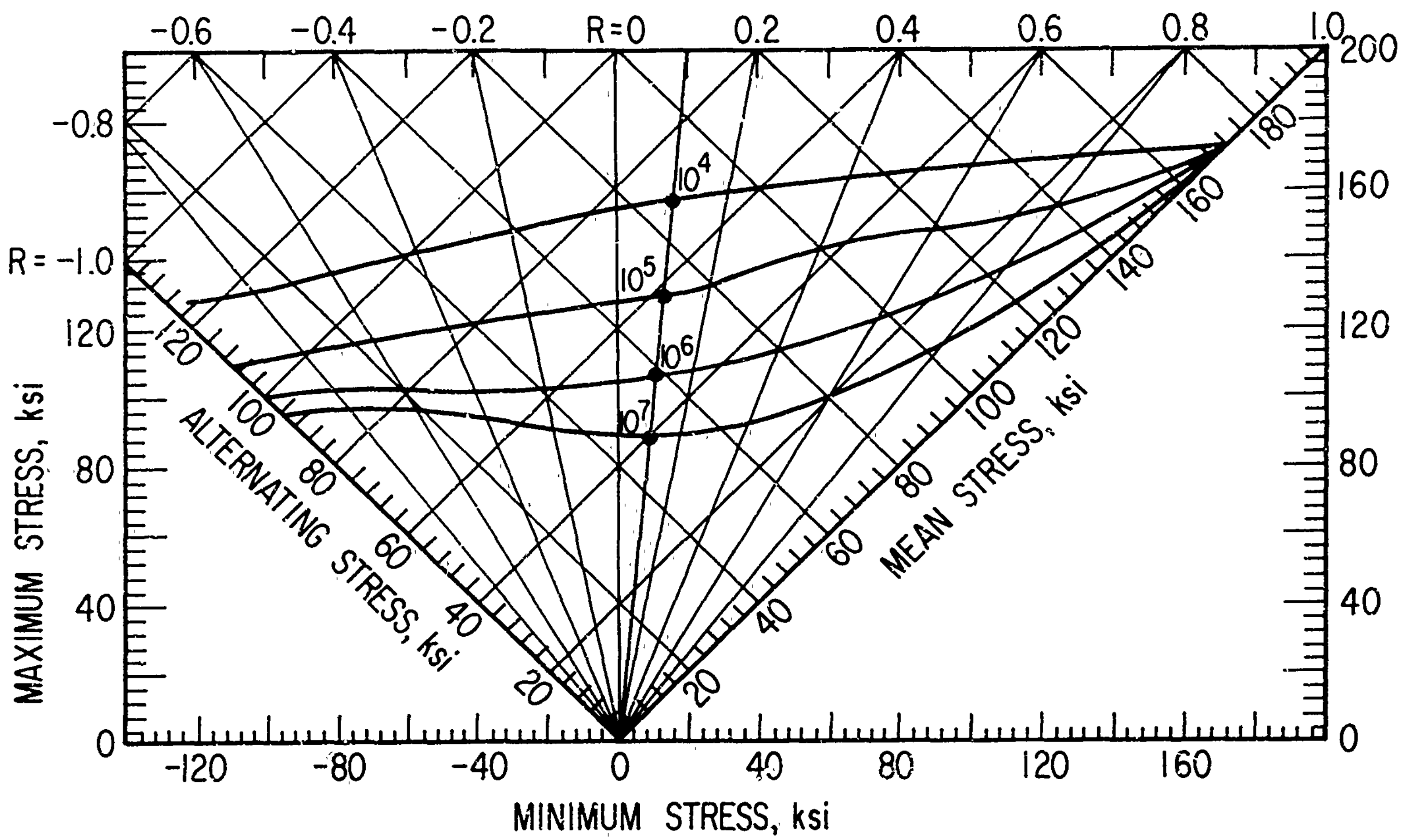


Fig. 42. Master Diagram of Unnotched, STA Forgings (Ref. 21)

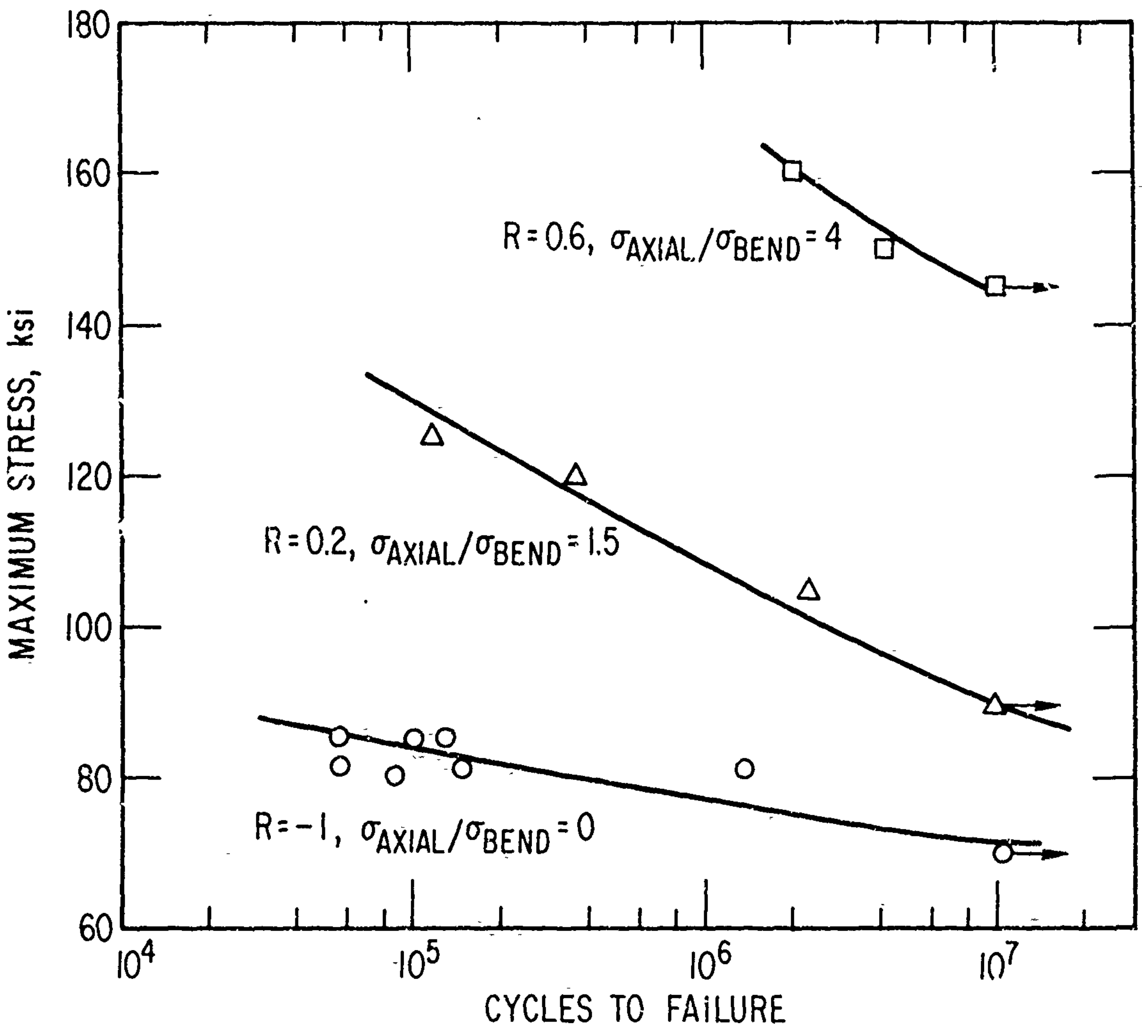


Fig. 43. Unnotched, S-N Behavior of STA Forgings Tested Under Combined Axial and Bending Stress (Material No. 29, Ref. 12)

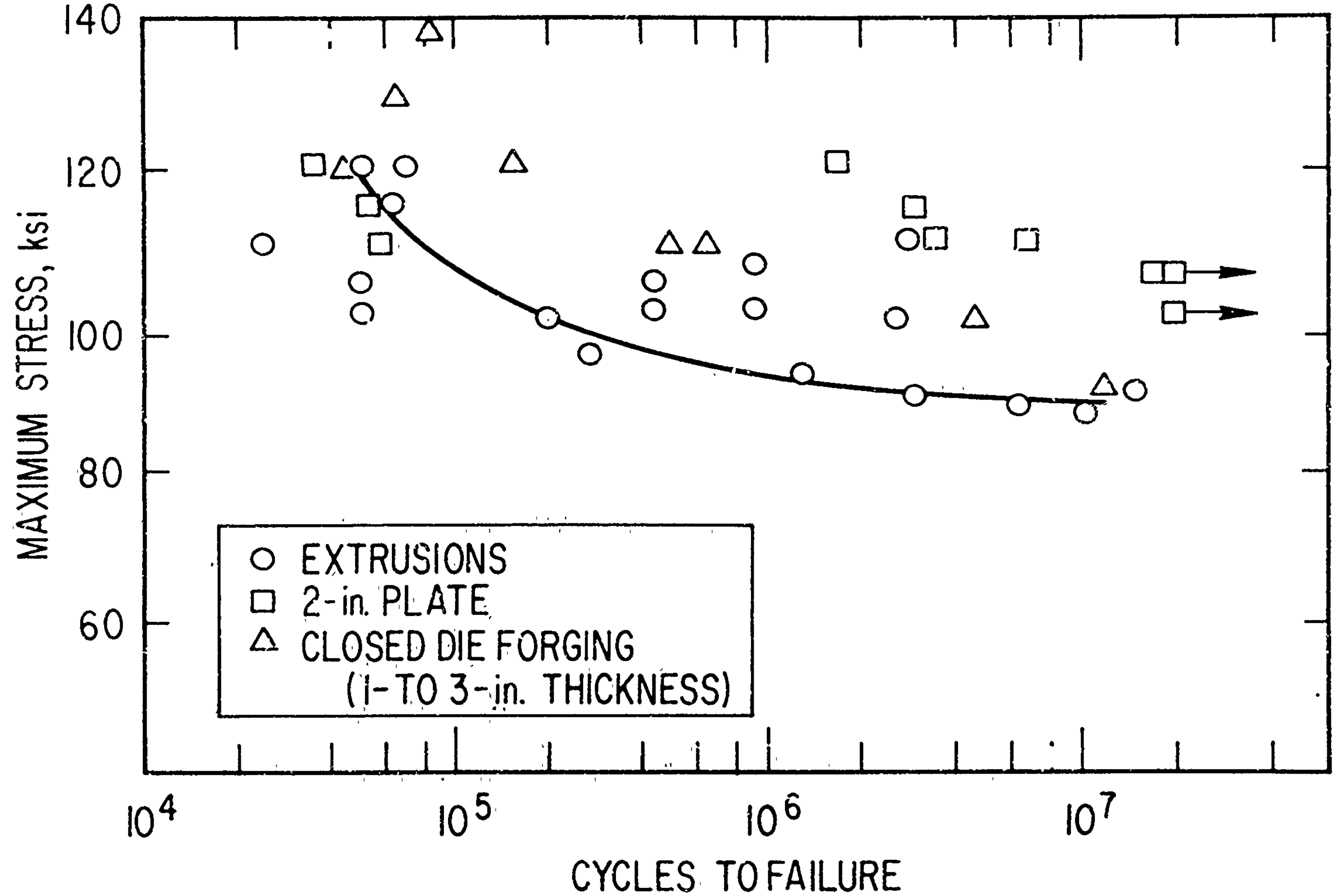


Fig. 44. Unnotched, S-N Behavior of STA Extrusions Compared With Plate and Forgings (R = 0.1, Material No. 33, Ref. 3)

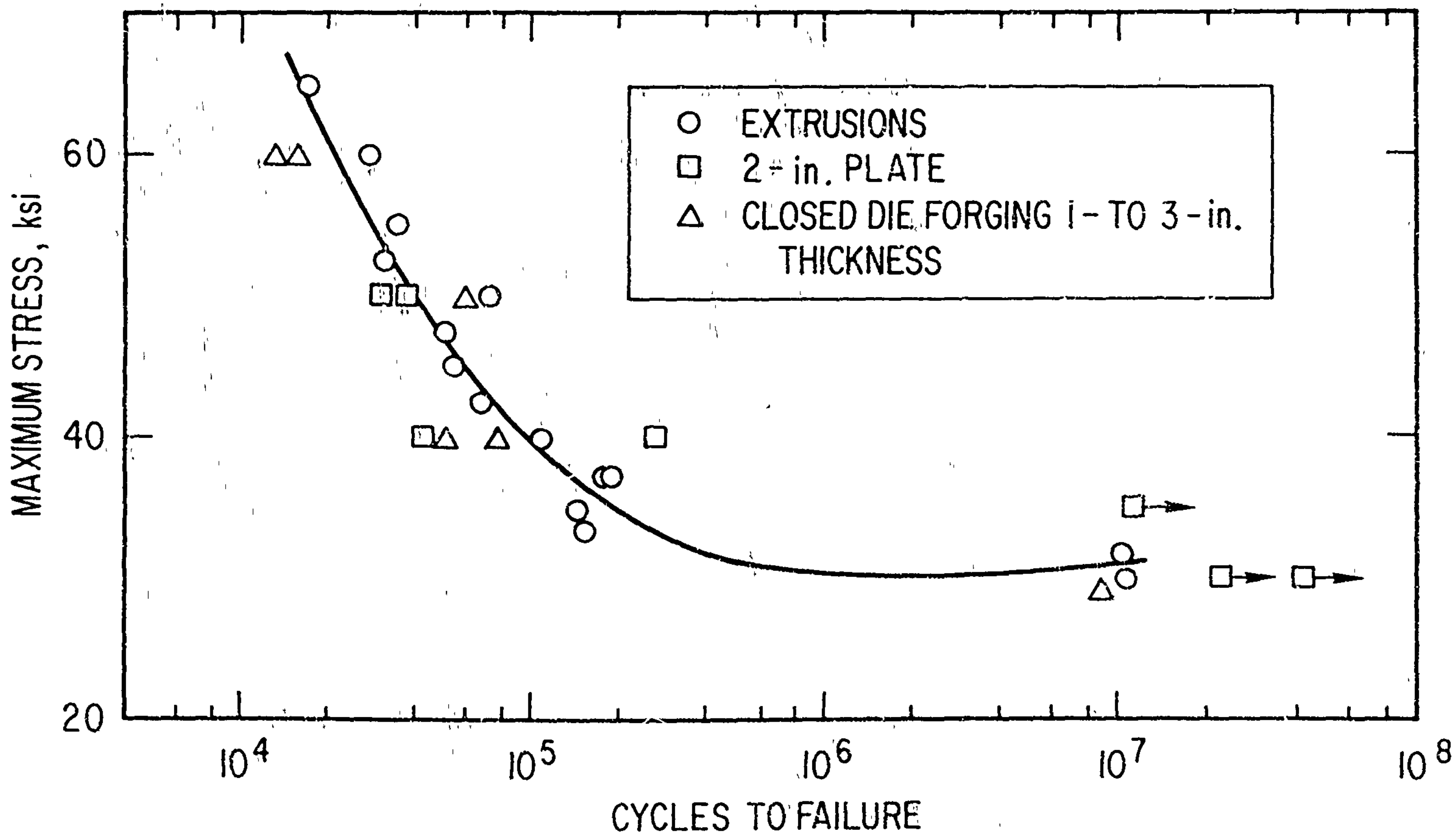


Fig. 45. Notched, S-N Behavior of STA Extrusions Compared With Plate and Forgings (K_T = 3.3, R = 0.1, Material No. 33, Ref. 3)

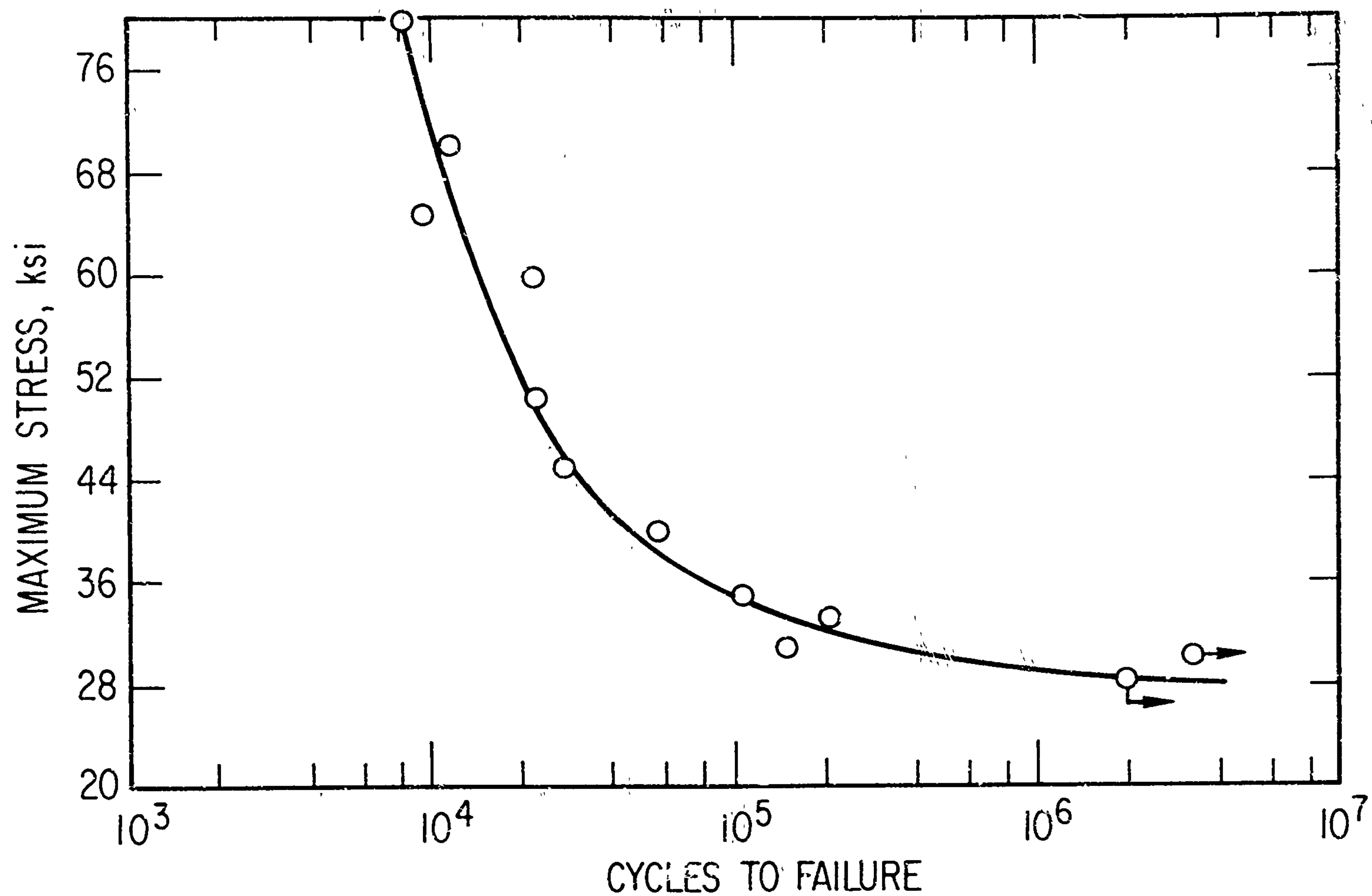
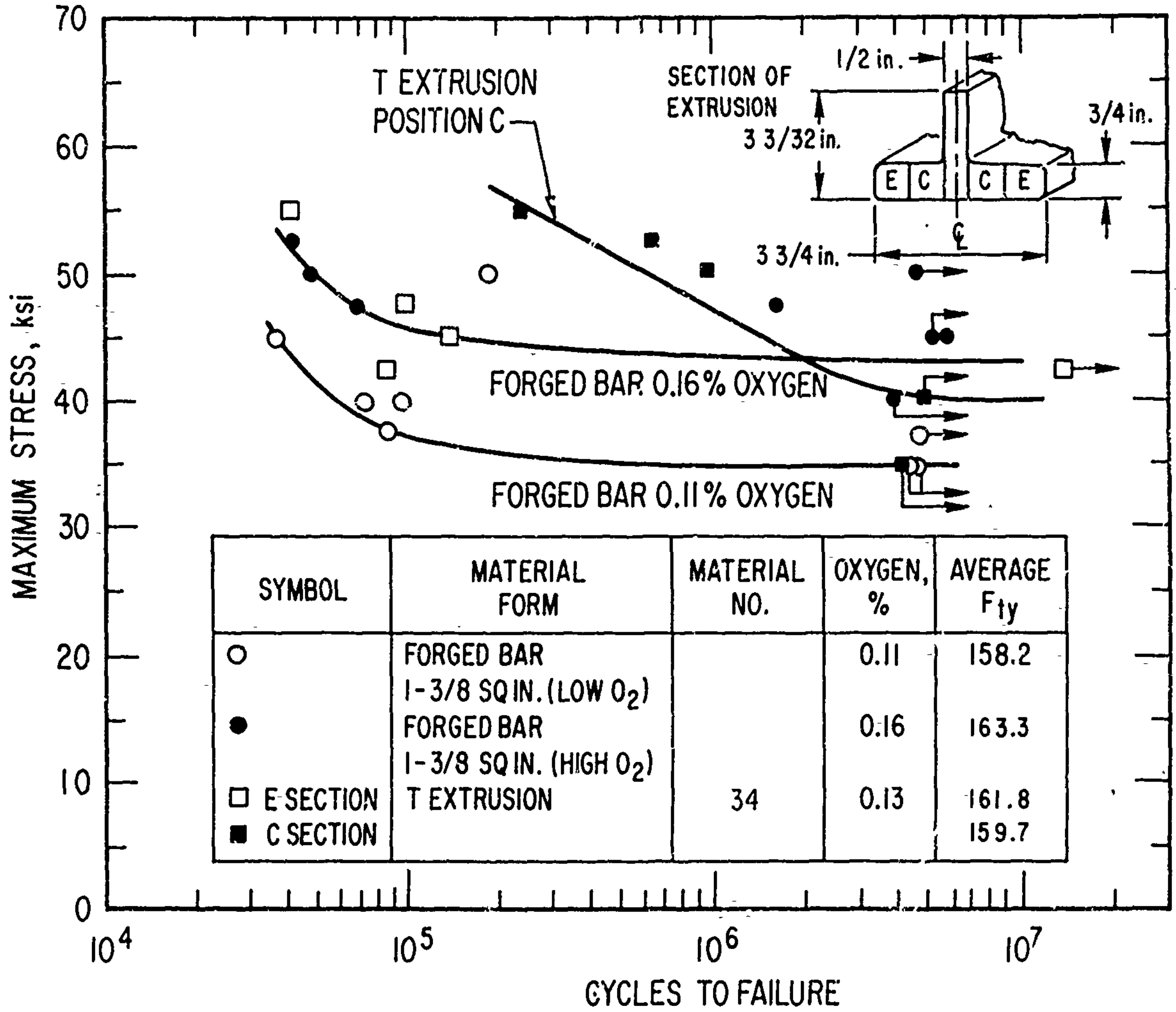


Fig. 46. Notched, S-N Behavior of STA Extrusions (K_T = 2.7, R = 0.1, Material No. 34, (Ref. 7)



SYMBOL	MATERIAL FORM	MATERIAL NO.	OXYGEN, %	AVERAGE F_{ty}
○	FORGED BAR 1-3/8 SQ IN. (LOW O_2)		0.11	158.2
●	FORGED BAR 1-3/8 SQ IN. (HIGH O_2)		0.16	163.3
□ E SECTION	T EXTRUSION	34	0.13	161.8
■ C SECTION				159.7

Fig. 47. Notched, S-N Behavior of STA Extrusions Compared With Bar (K_T = 3.3, R = 0.1, Material No. 34, Ref. 7)

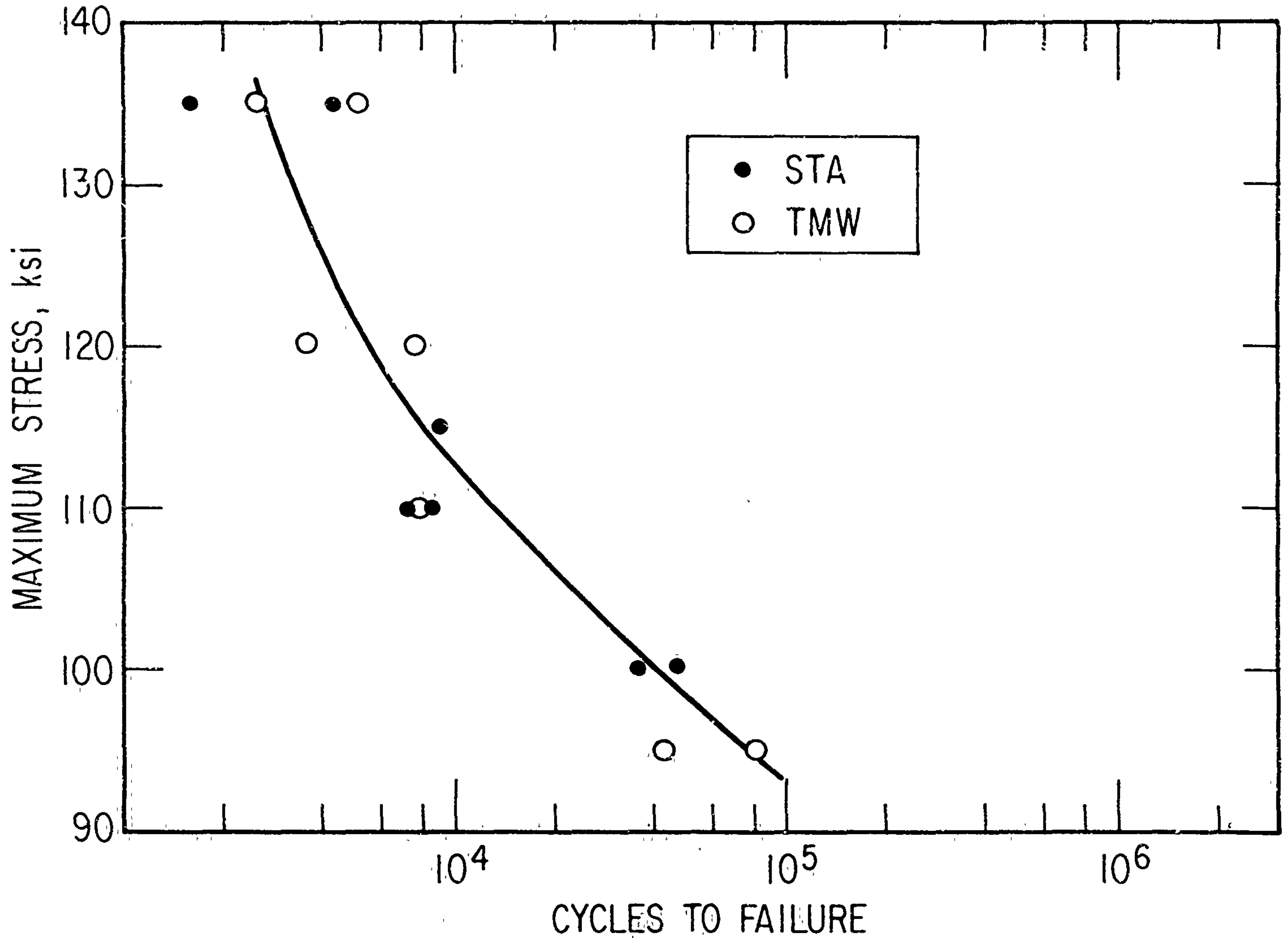


Fig. 48. Unnotched, S-N Behavior of TMW Material Compared With STA Forgings (Constant Mean Stress = 60 ksi, Material No. 37, Ref. 19)

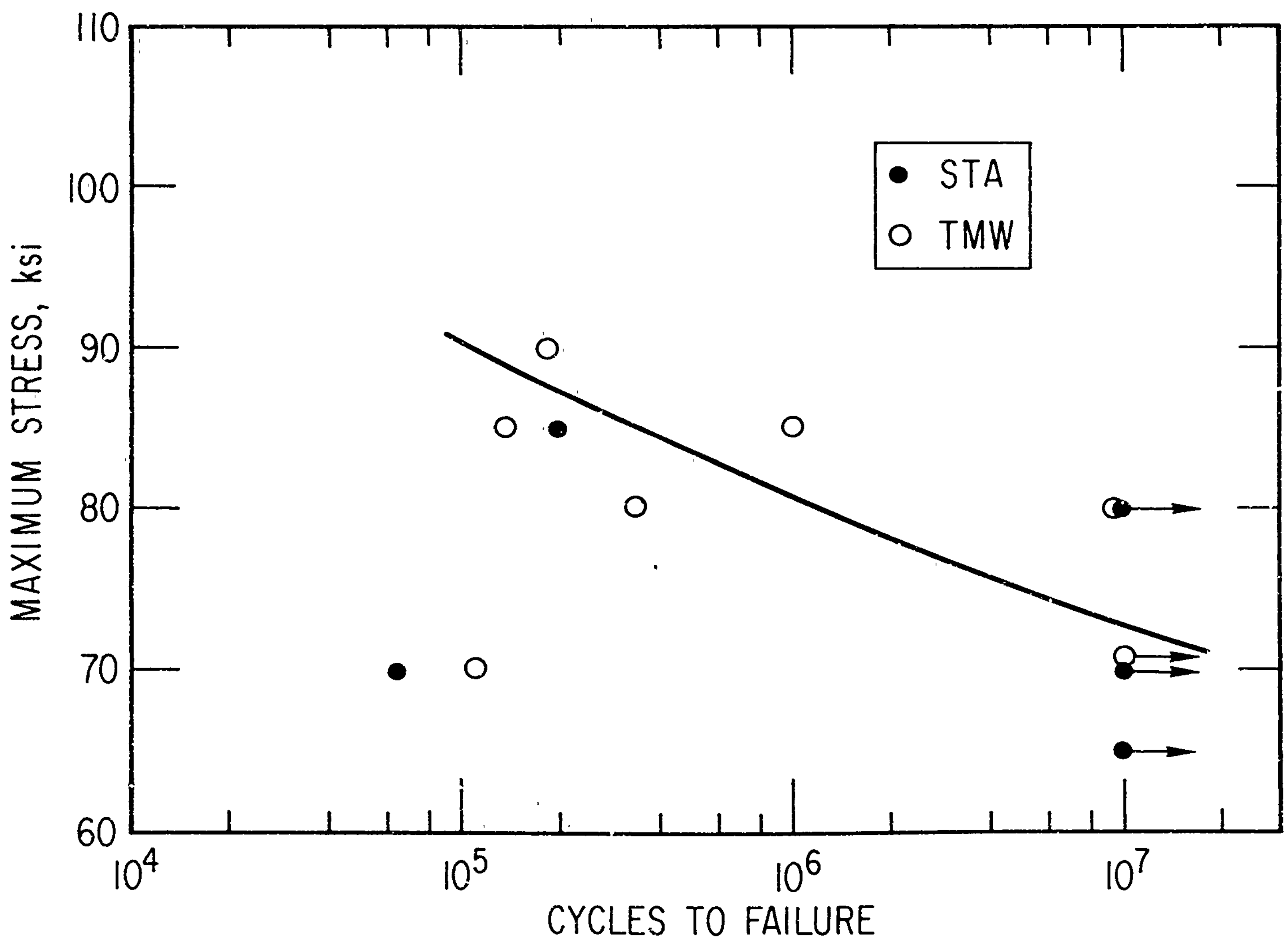


Fig. 49. Unnotched, S-N Behavior of TMW Forgings (R = -1, Material No. 37, Ref. 18)

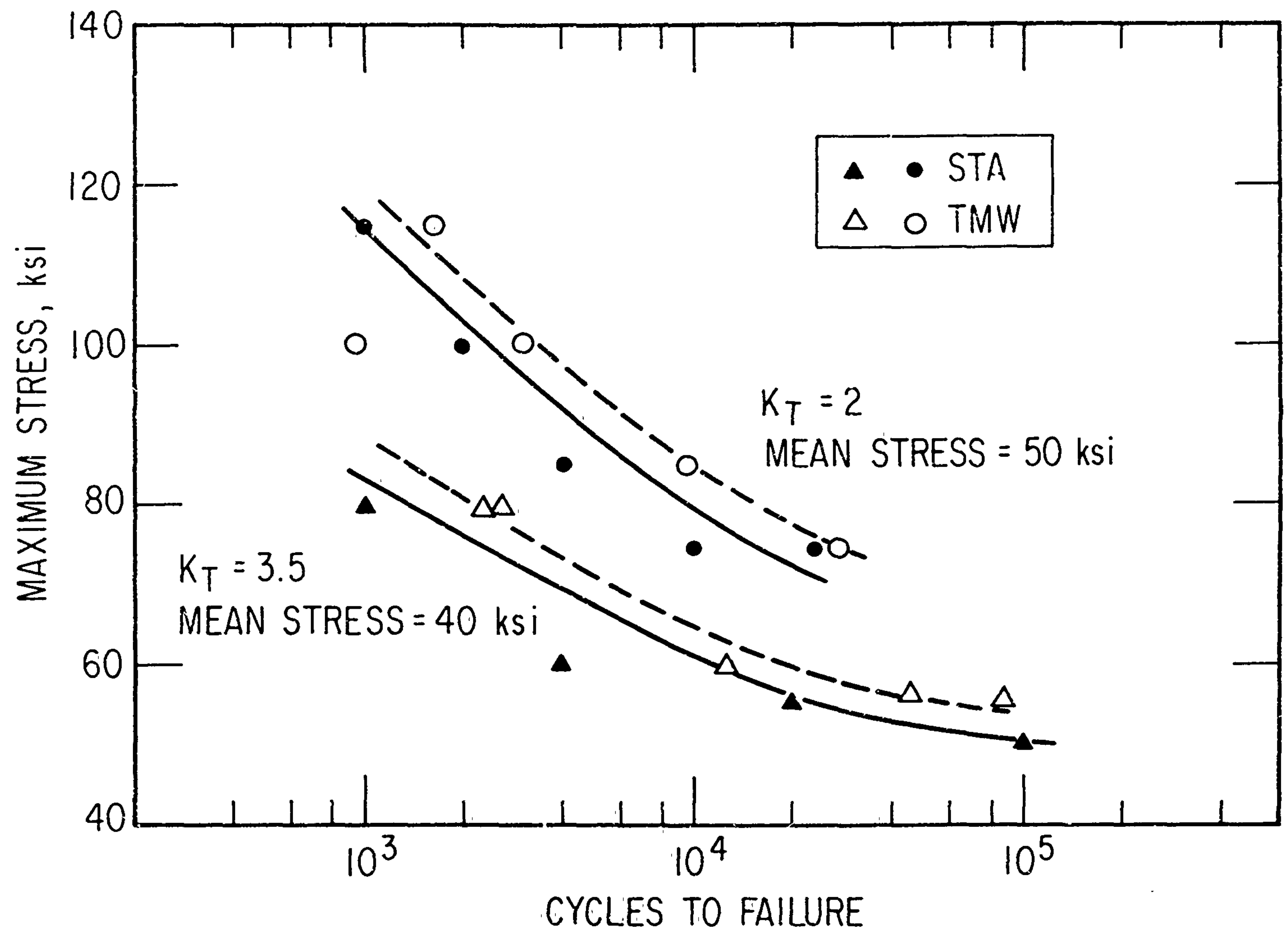


Fig. 50. Notched, S-N Behavior of TMW Forgings Compared With STA Forgings (Material No. 37, Ref.18).

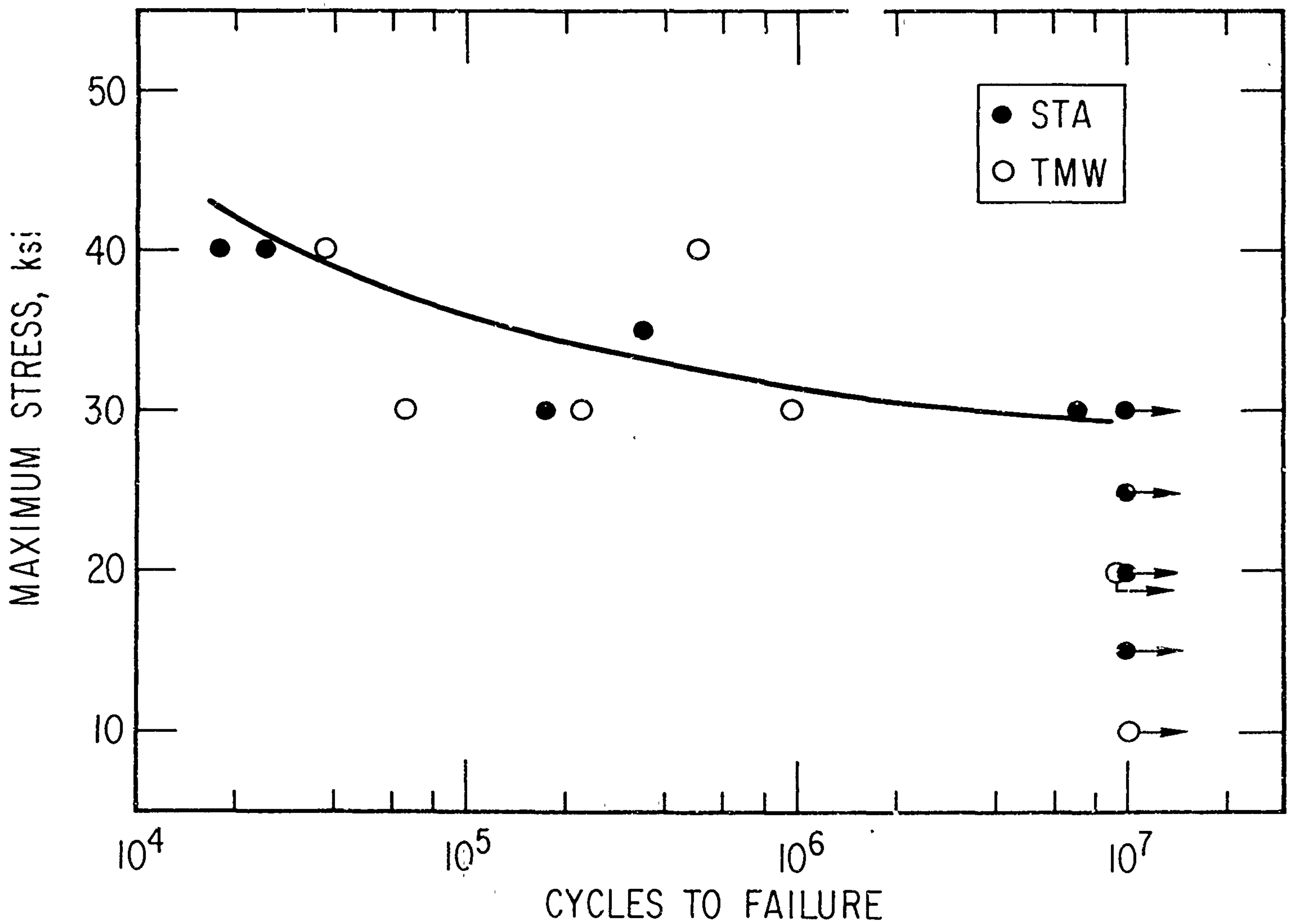


Fig. 51. Notched, S-N Behavior of TMW Forgings (R = -1, Material No. 37, Ref. 18)

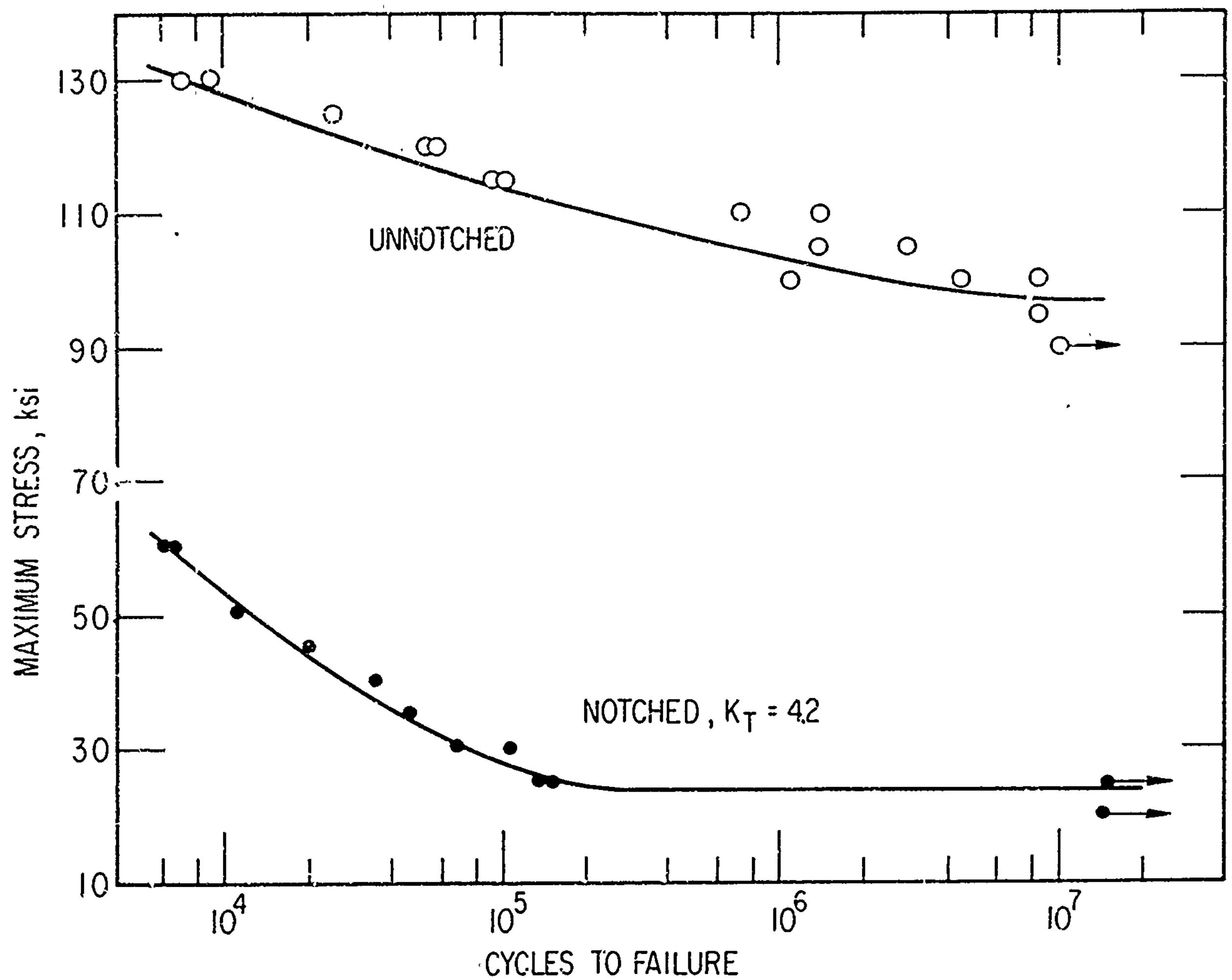


Fig. 52. Notched and Unnotched, S-N Behavior of Annealed Sheet at 450°F (R = 0.1, Material No. 14, Ref. 15)

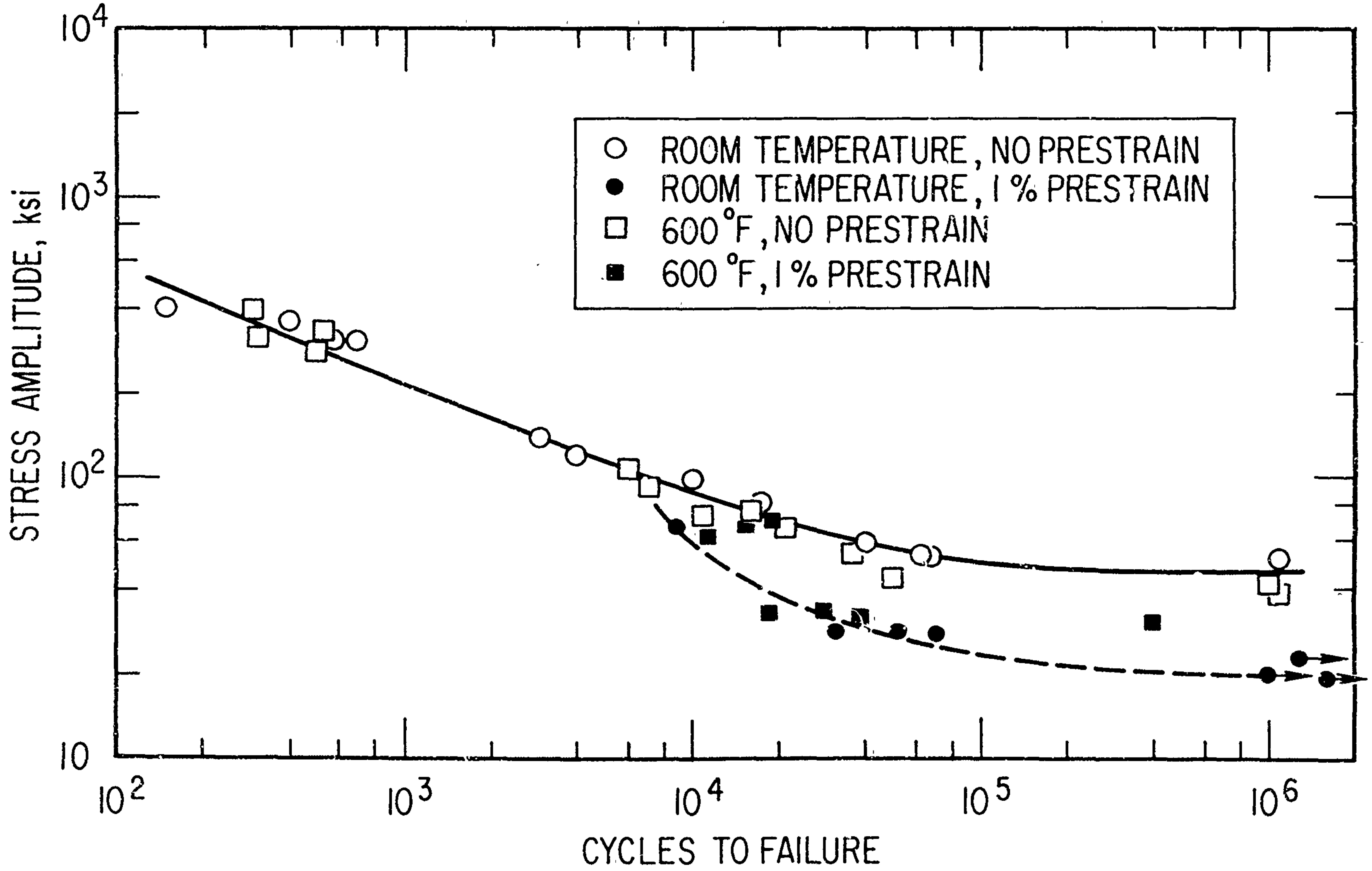


Fig. 53. Unnotched, S- N Behavior for Annealed Bar at Room Temperature and 600°F (Material No. 8, Ref. 9)

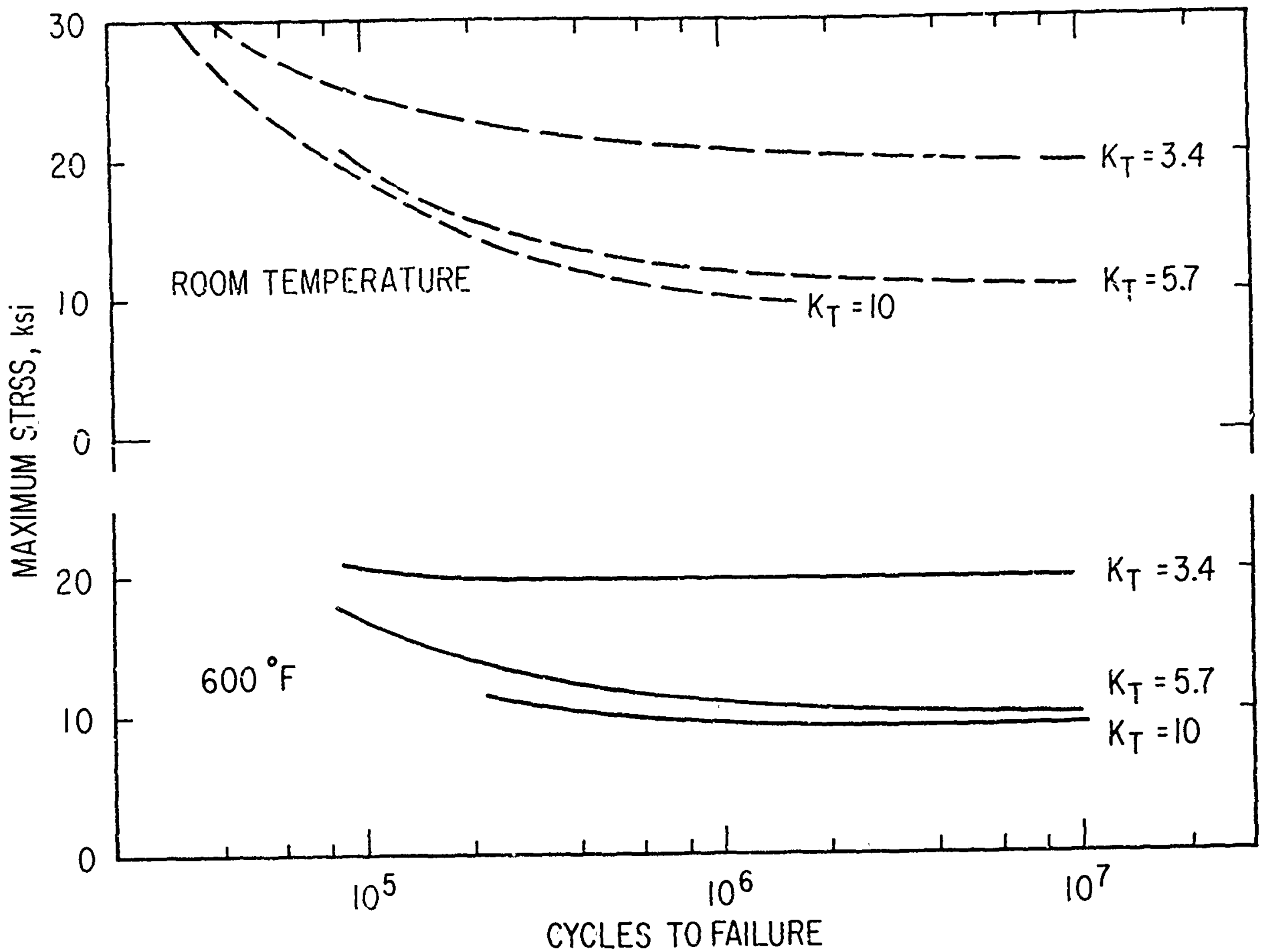


Fig. 54. Notched, S-N Behavior for Annealed Bar at Room Temperature and 600°F (Material No. 8, Ref. 9)

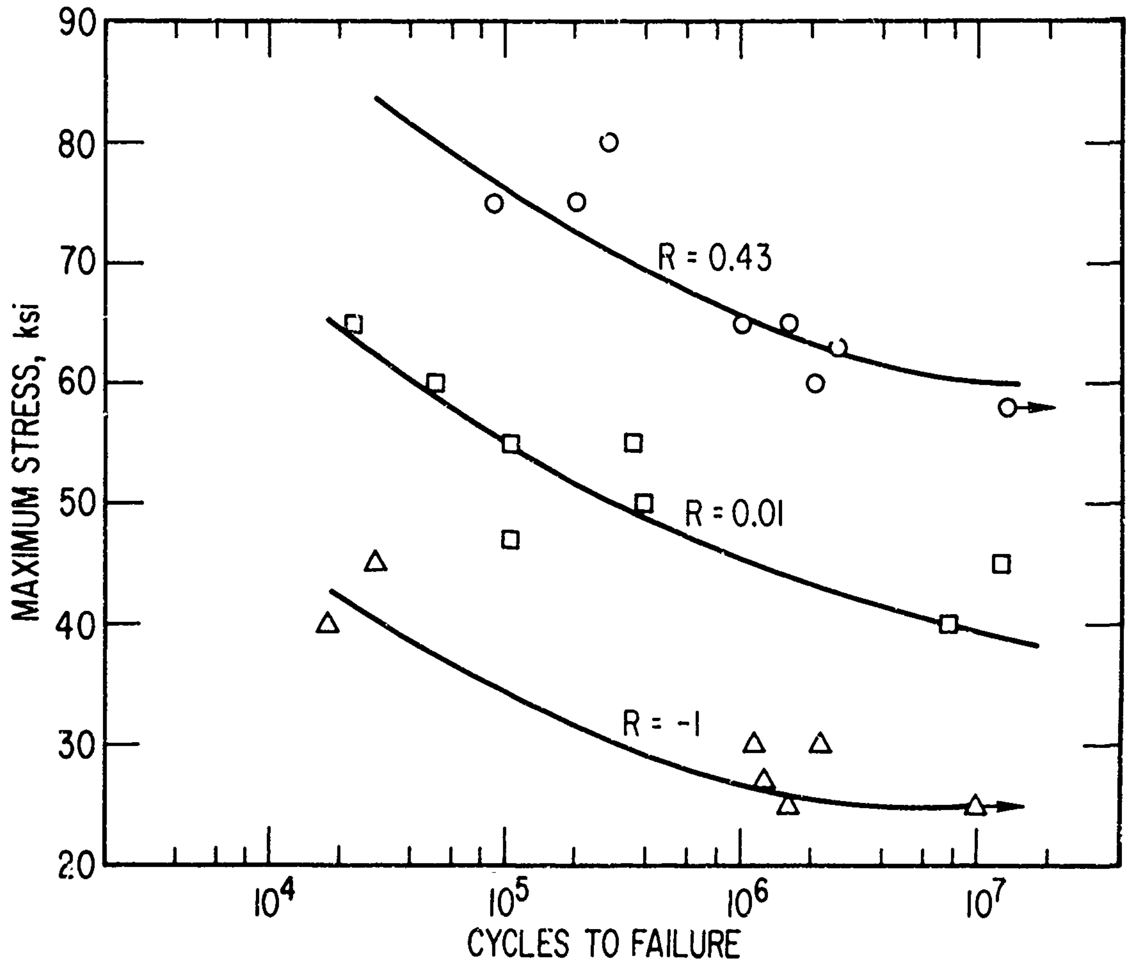


Fig. 55. Notched, S-N Behavior of Annealed Extrusions at 400°F (K_T = 2.76, Material No. 12, Ref. 22)

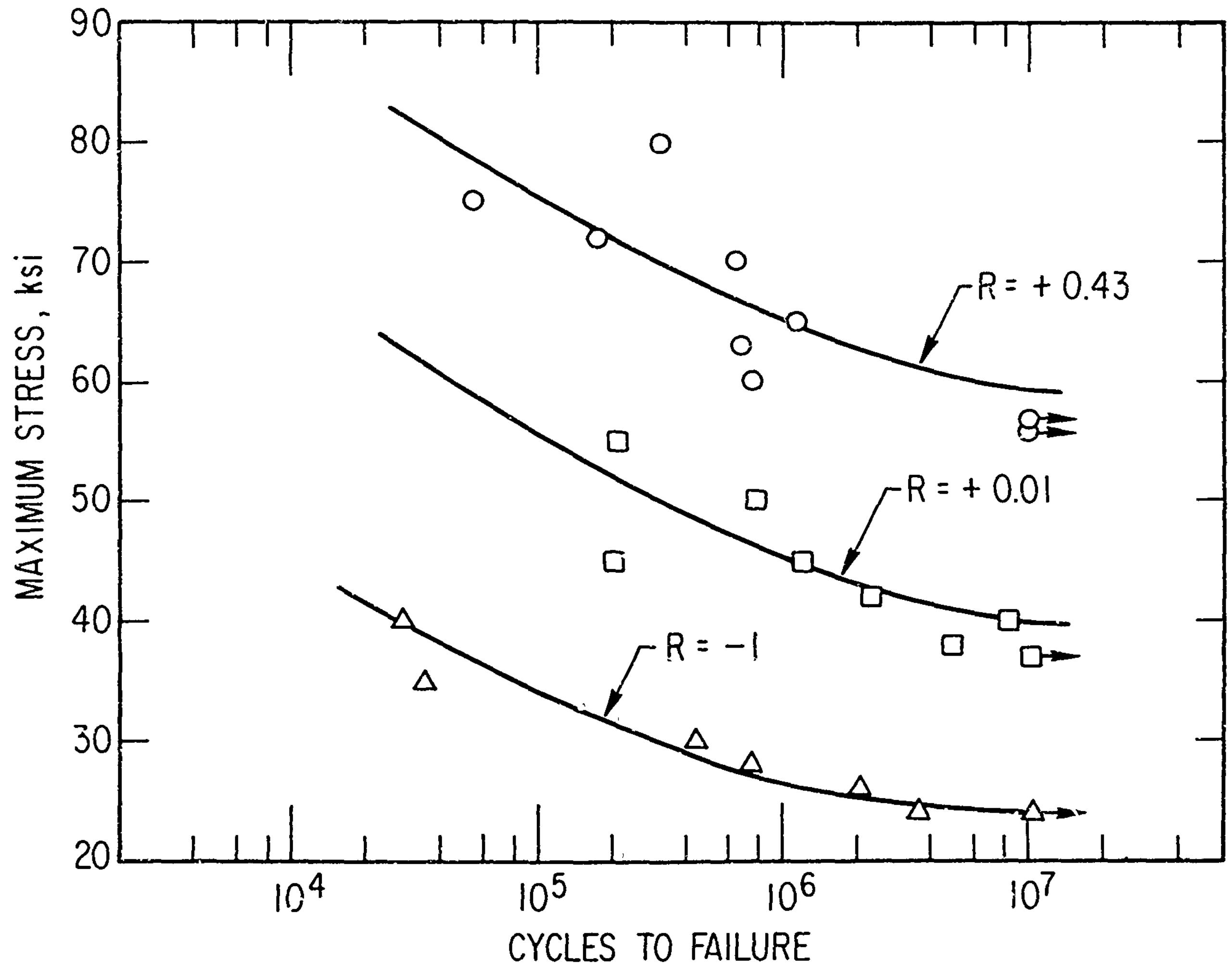


Fig. 56. Notched, S-N Behavior of Annealed Extrusions at 600°F (K_T = 2.76, Material No. 12, Ref. 22)

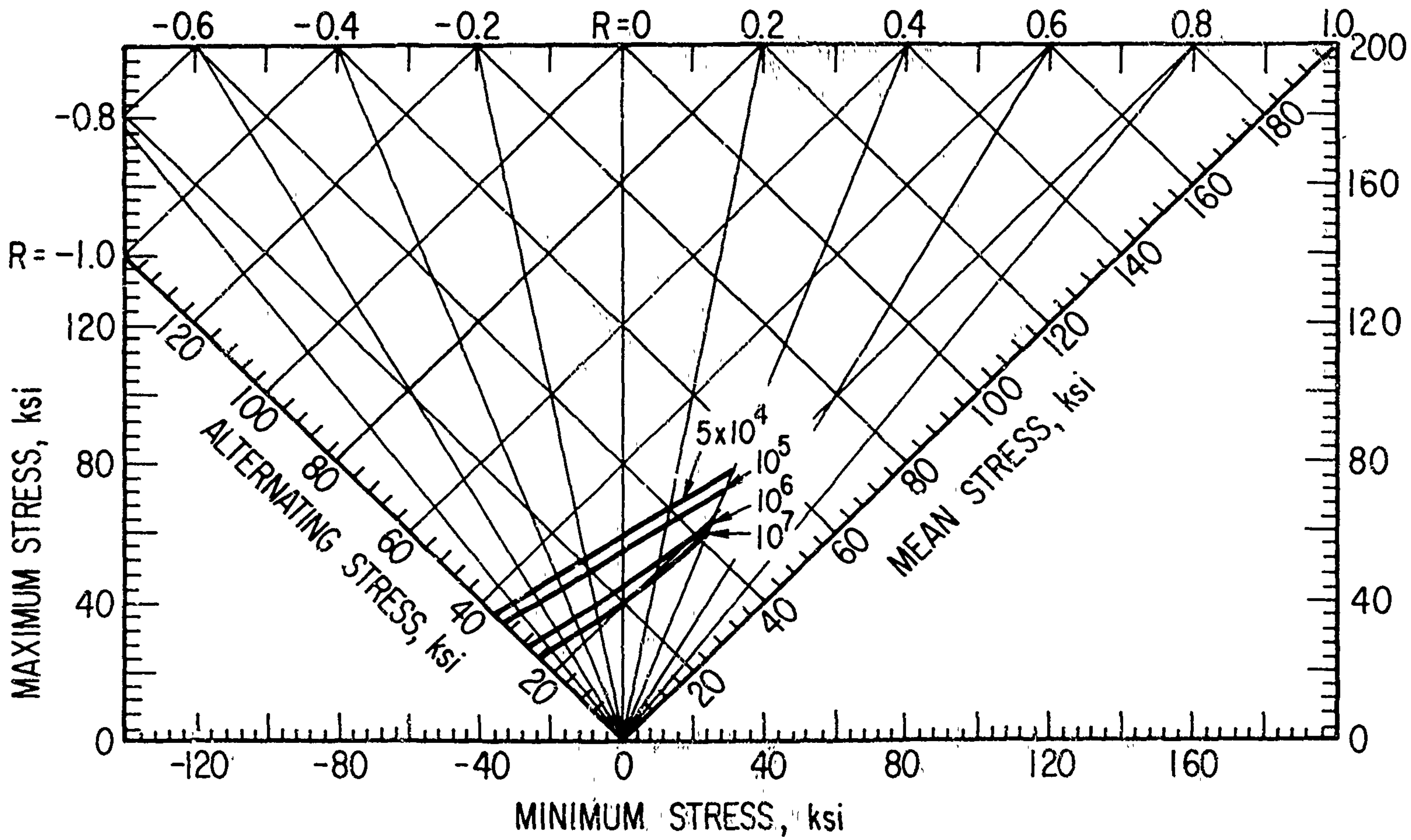


Fig. 57. Master Diagram of Notched, Annealed Extrusions at 400 and 600°F (K_T = 2.75, Material No. 12, Ref. 22)

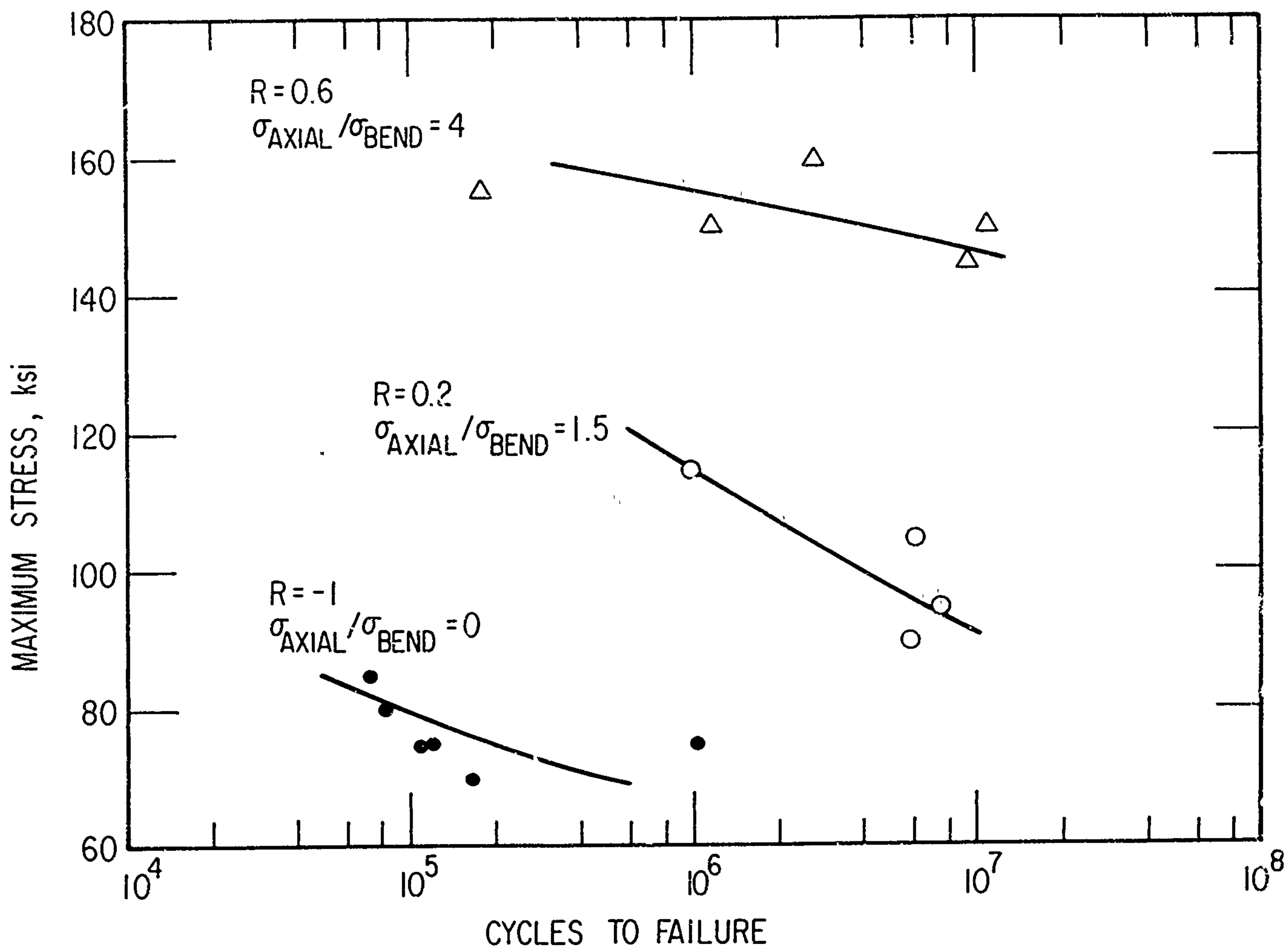


Fig. 58. Unnotched, S-N Behavior of STA Forgings Tested Under Combined Axial and Bending Stress at 300°F (Material No. 29, Ref 14)

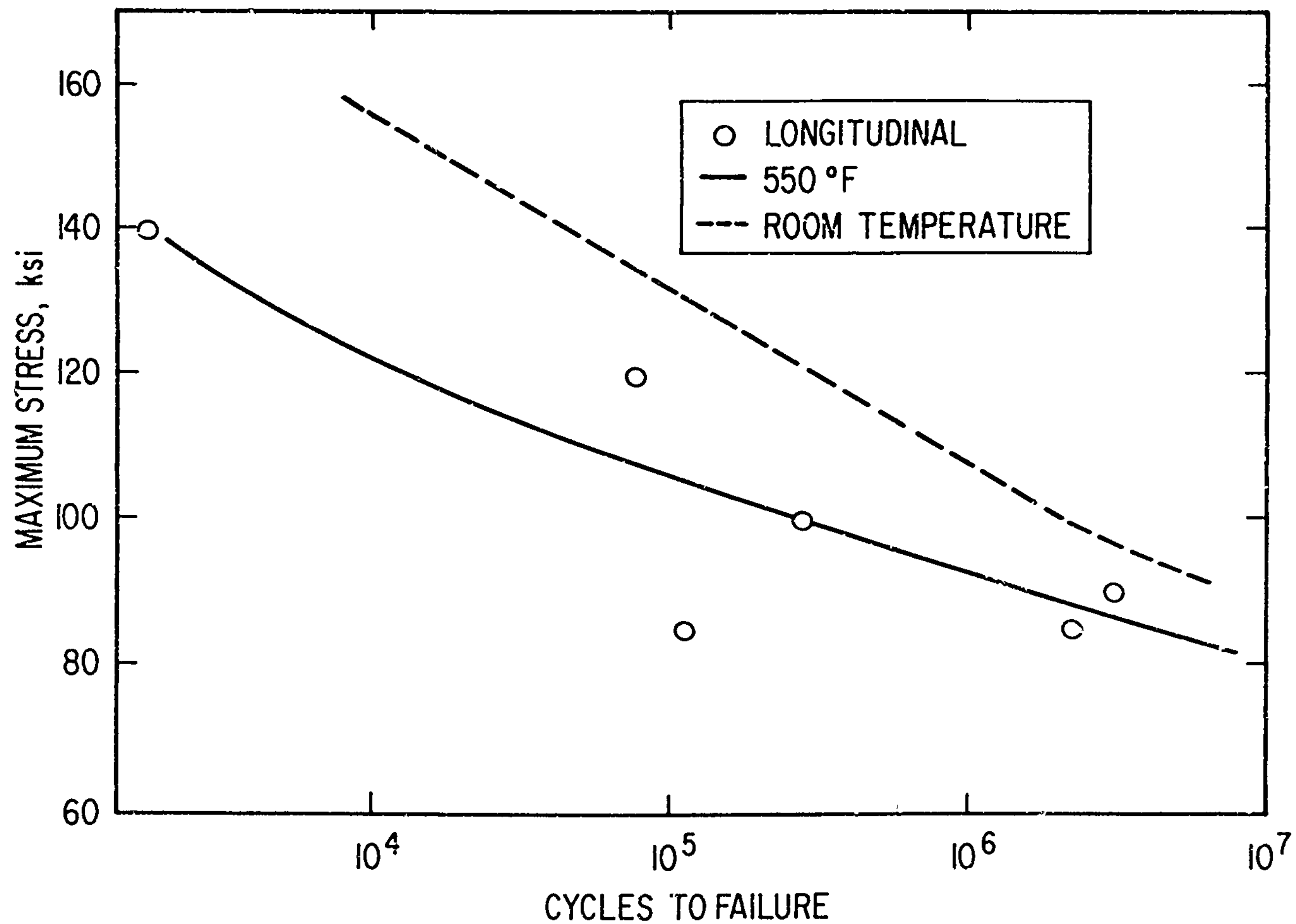


Fig. 59. Unnotched, S-N Behavior of STA Forgings at 550°F (Material No. 28, Refs. 5 and 6)

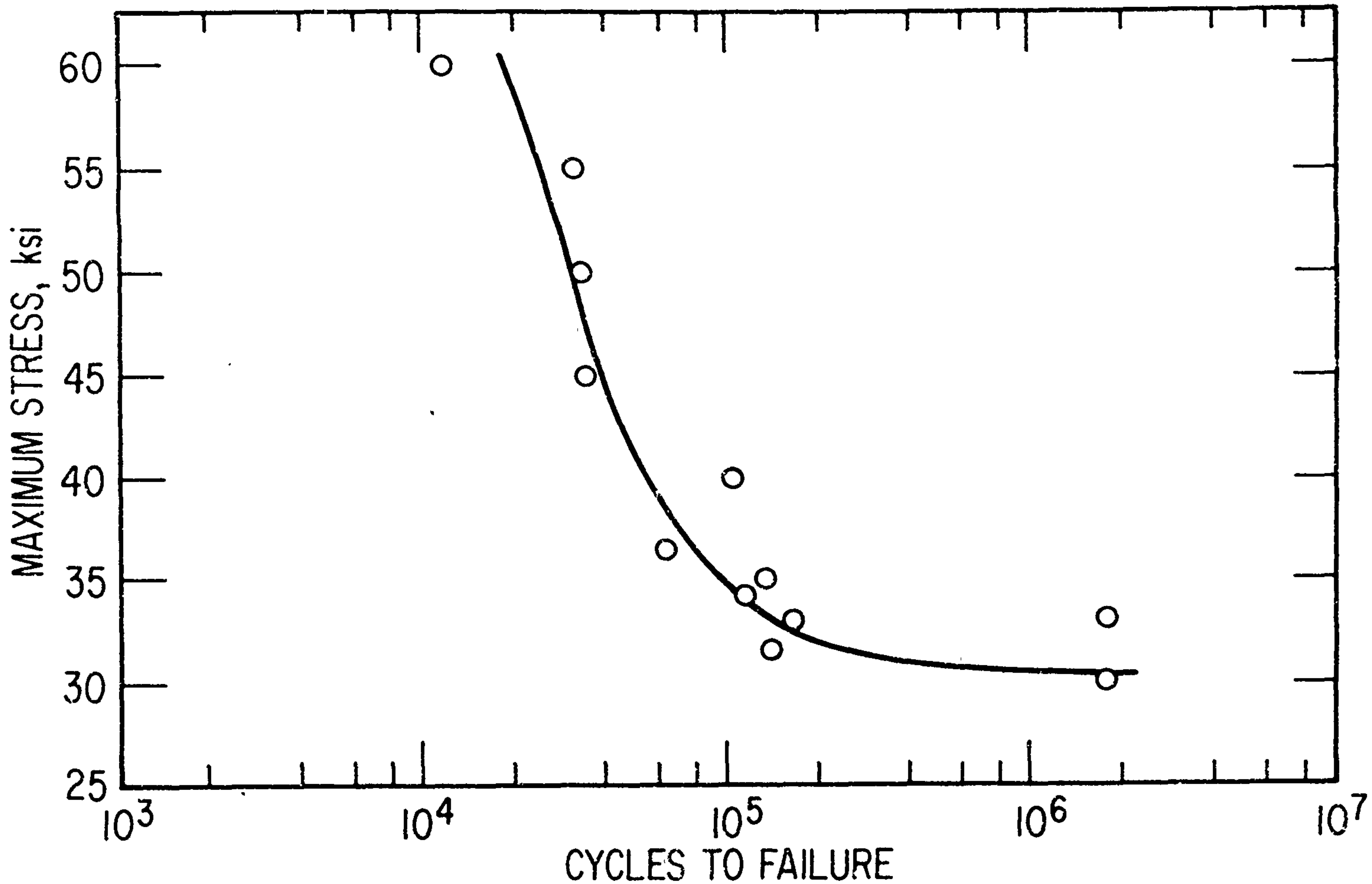


Fig. 60. Notched, S-N Behavior of STA Extrusions at 400°F (K_T = 2.7, R = 0.1, Material No. 33, Ref. 8)

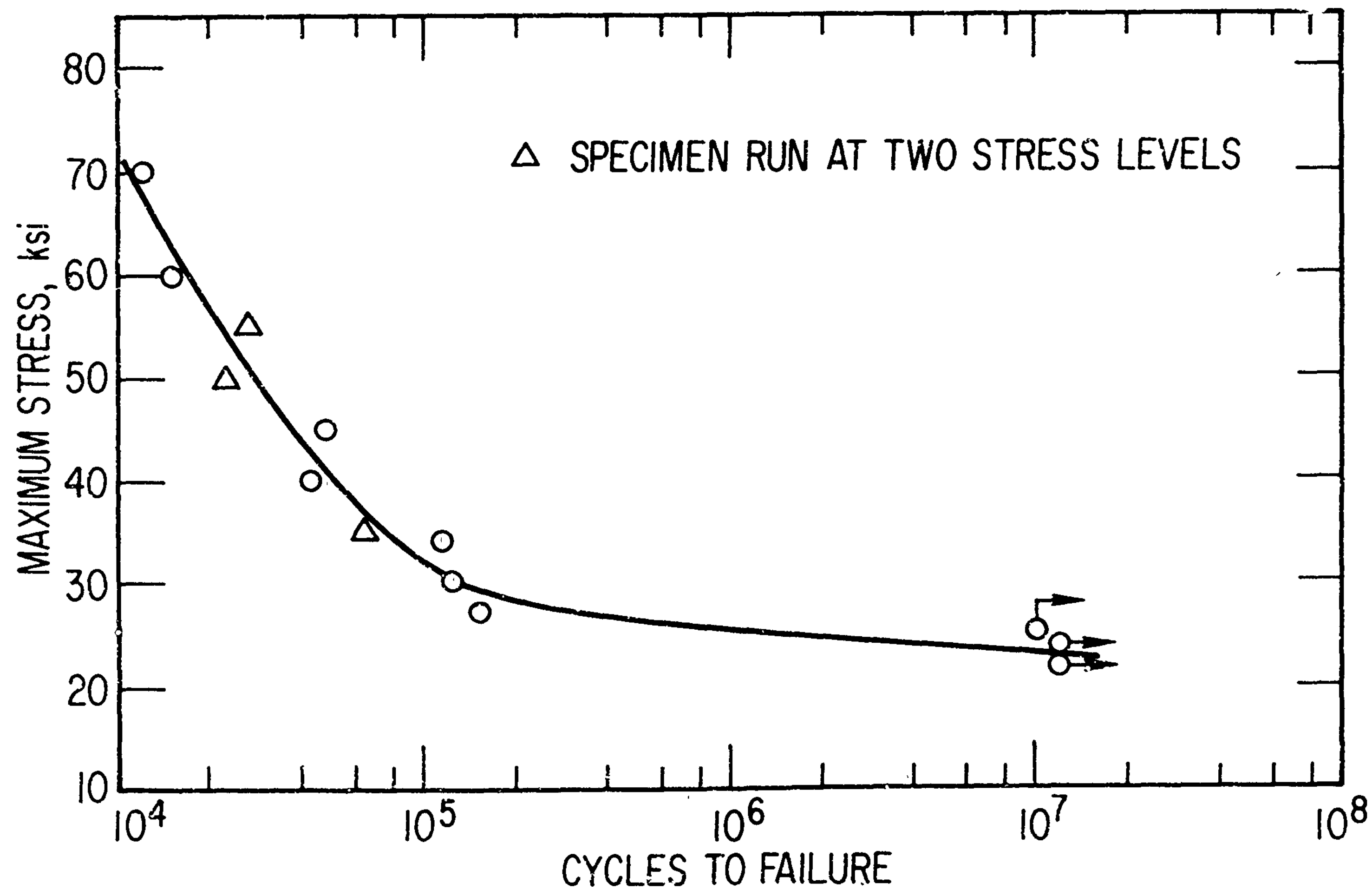


Fig. 61. Notched, S-N Behavior of STA Extrusions at 550°F (K_T = 2.7, R = 0.1, Material No. 33, Ref. 8)

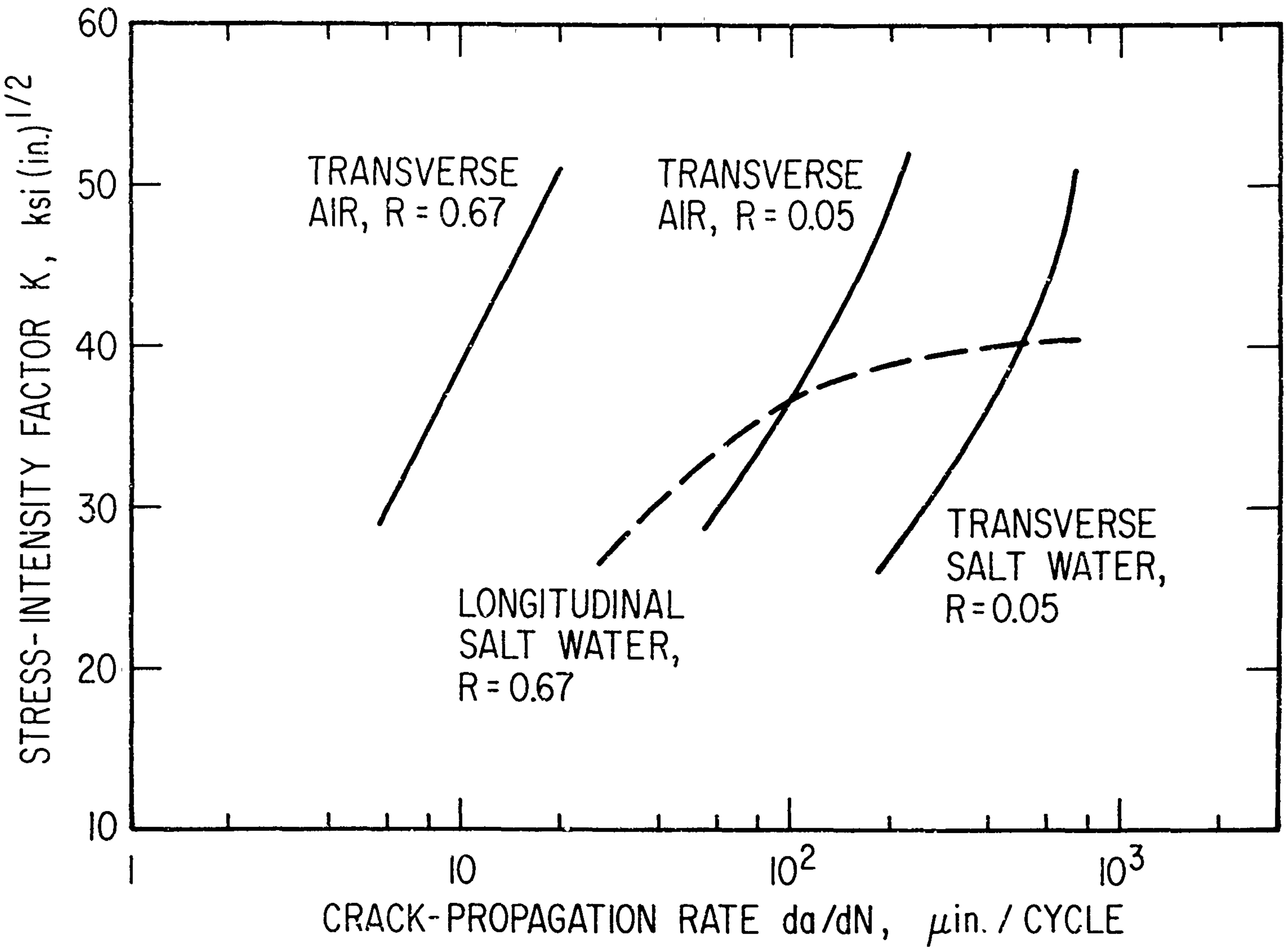


Fig. 62. Crack Growth of Annealed Sheet in Air and Salt Water (Material No. 1, Ref. 10)

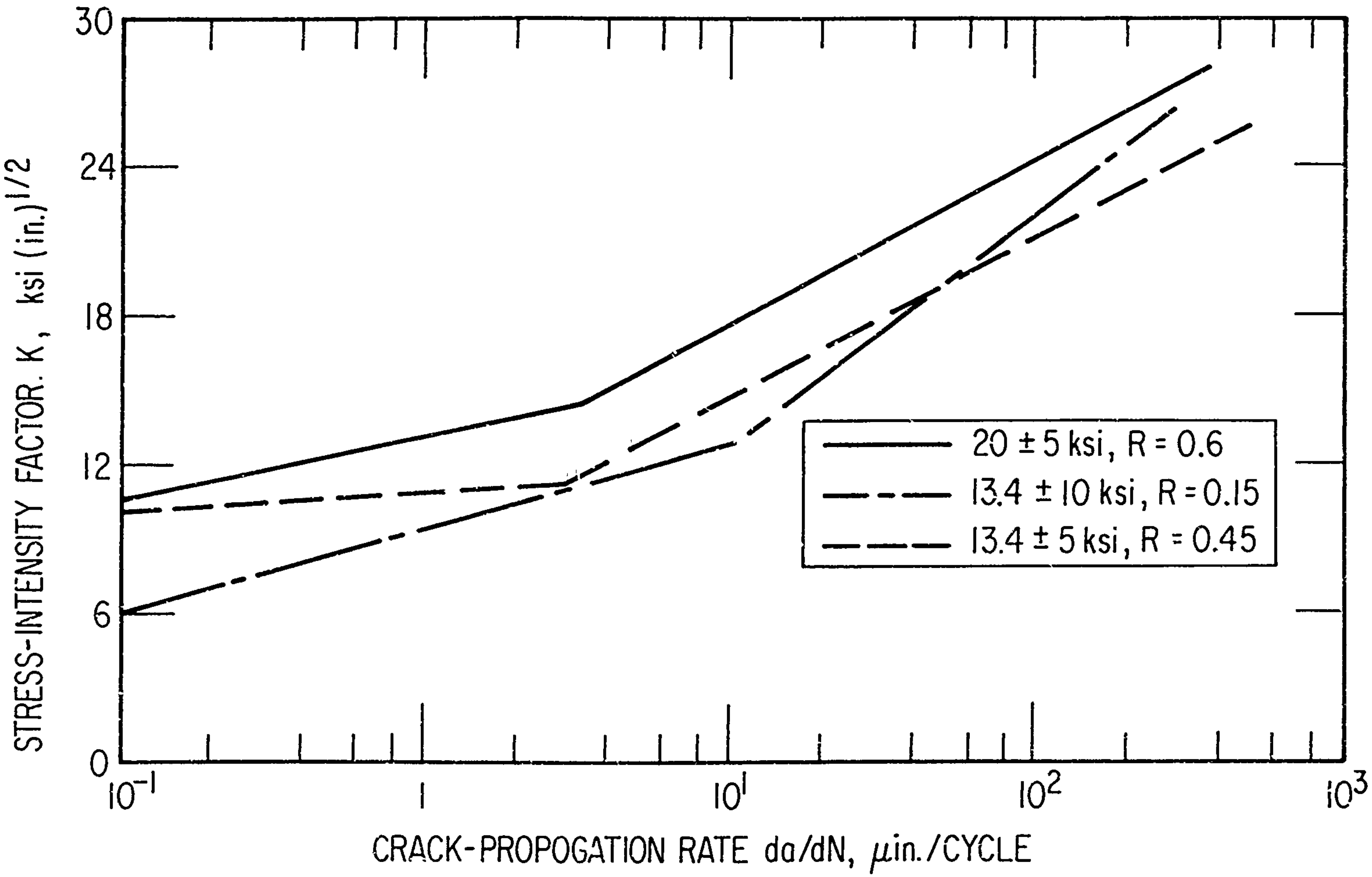


Fig. 63. Crack-Growth Behavior of STA Forging (Material No. 22, Ref. 11)

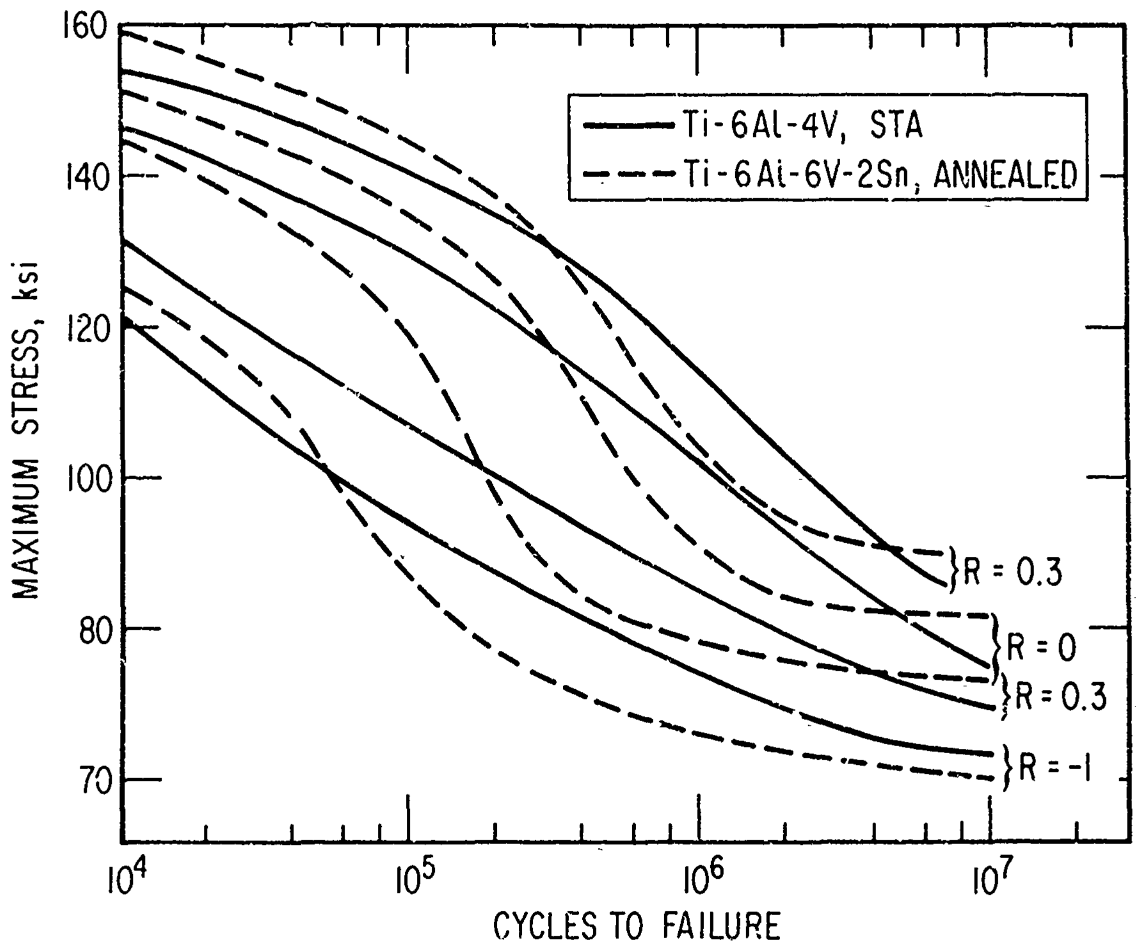


Fig. 64. Unnotched, S-N Behavior of Ti-6Al -4V Plate at Room Temperature in the STA Condition Compared With Ti-6Al-6V-2Sn Plate in the Annealed Condition (Ref. 21)

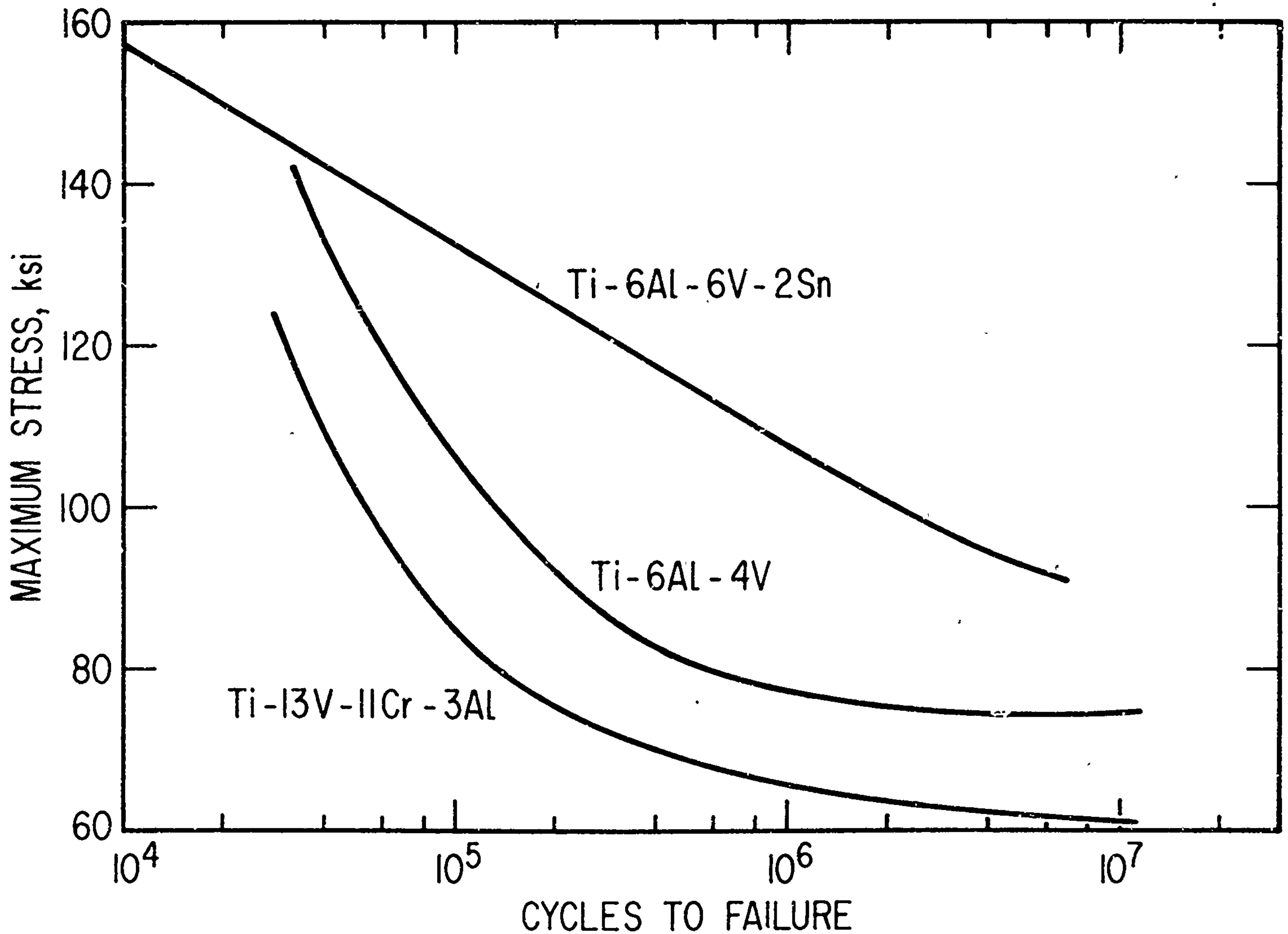


Fig. 65. Unnotched, S-N Behavior of Ti-6Al-4V STA Forgings at Room Temperature Compared With Ti-6Al-6V-2Sn (R = 0.1, Ref. 23)

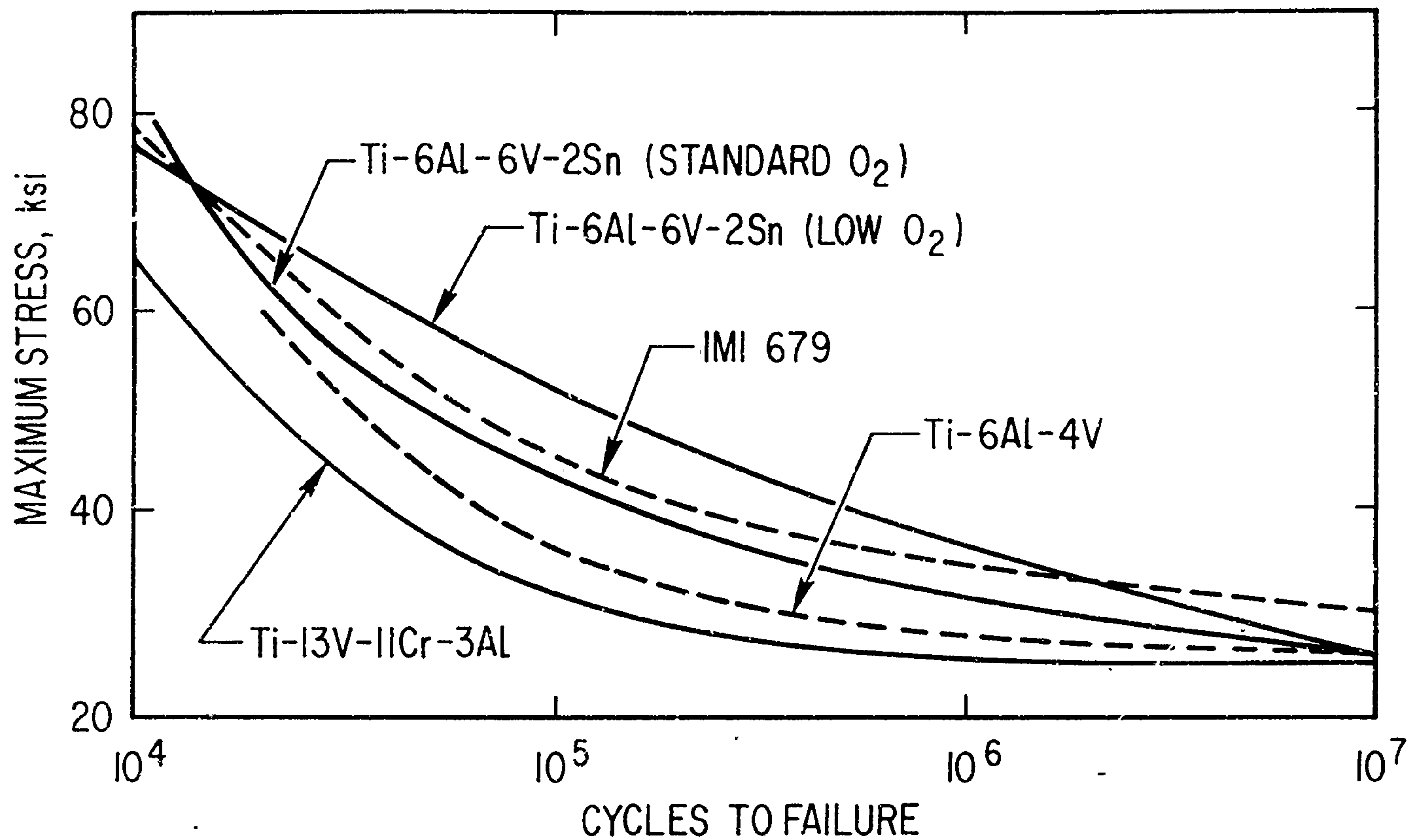


Fig. 66. Notched, S-N Behavior of STA Forgings Compared With Various Titanium Alloys (K_T = 3, R - 0.1, Ref. 23)

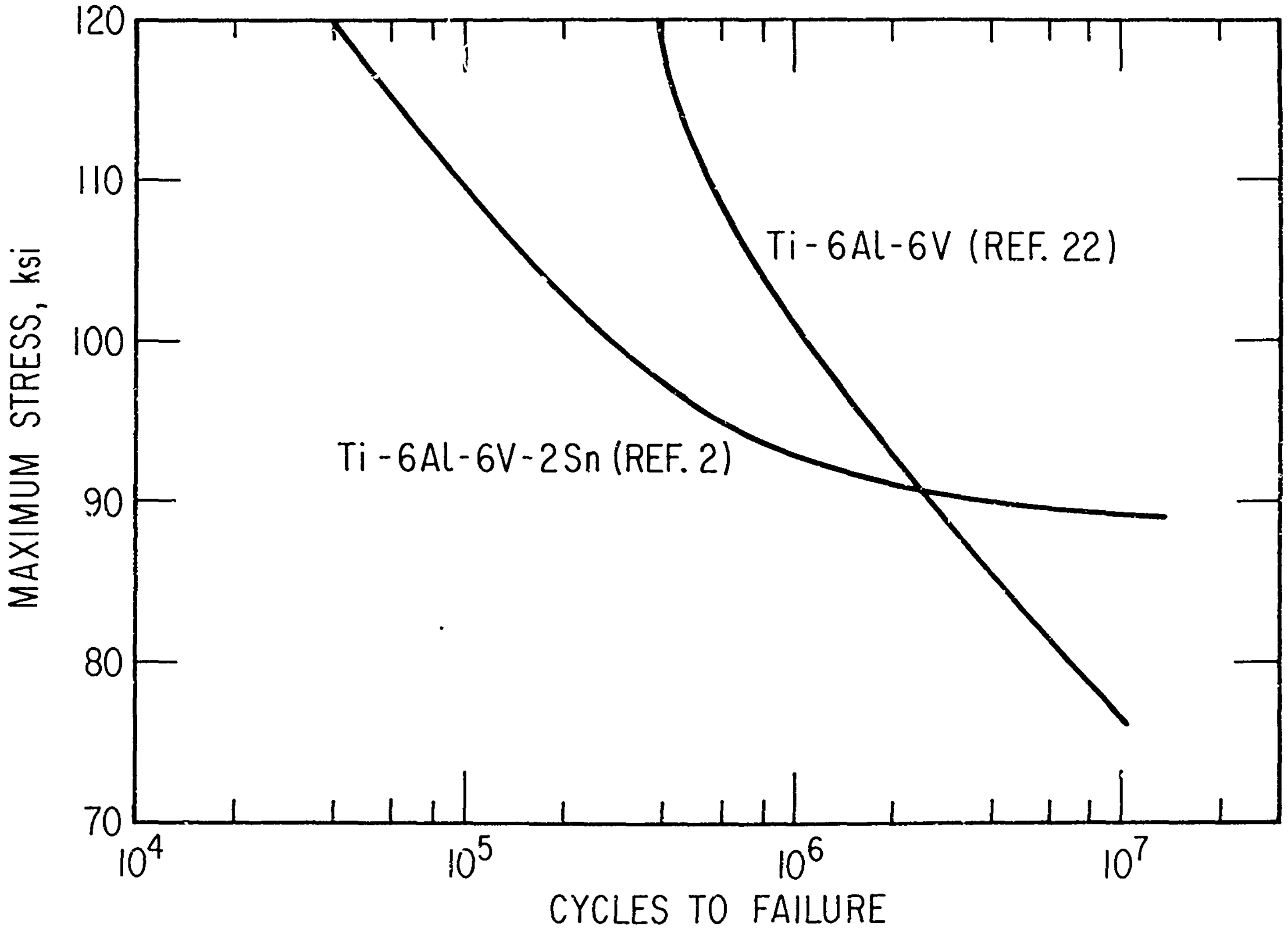


Fig. 67. Unnotched, S-N Behavior of Ti-6Al-4V STA Extrusions Compared With Ti-6Al-6V-2Sn (R = 0.1)

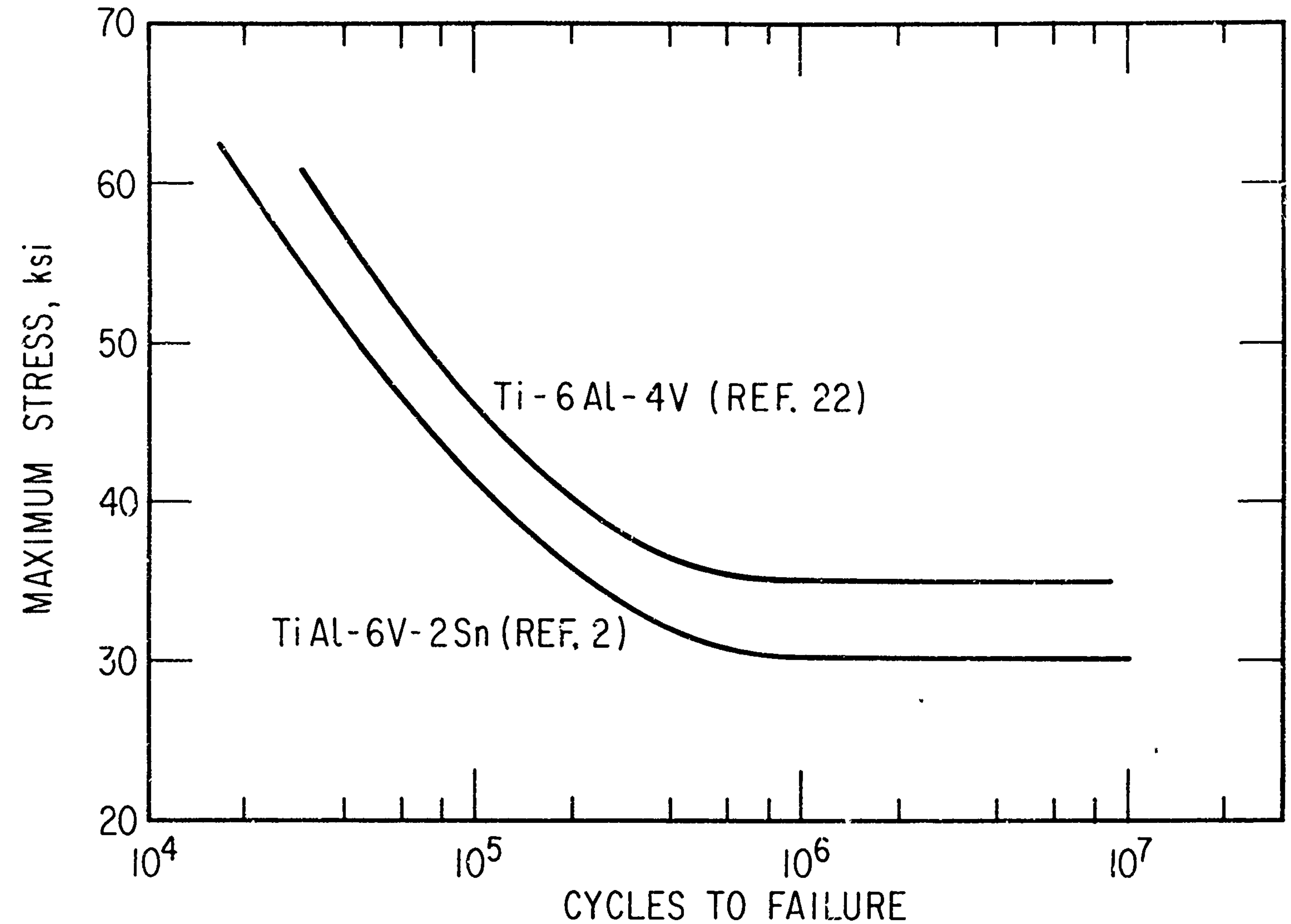


Fig. 68. Notched, S-N Behavior of Ti-6Al-4V STA Extrusions Compared With Ti-6Al-6V-2Sn (K_T = 3.3, R = 0.1)

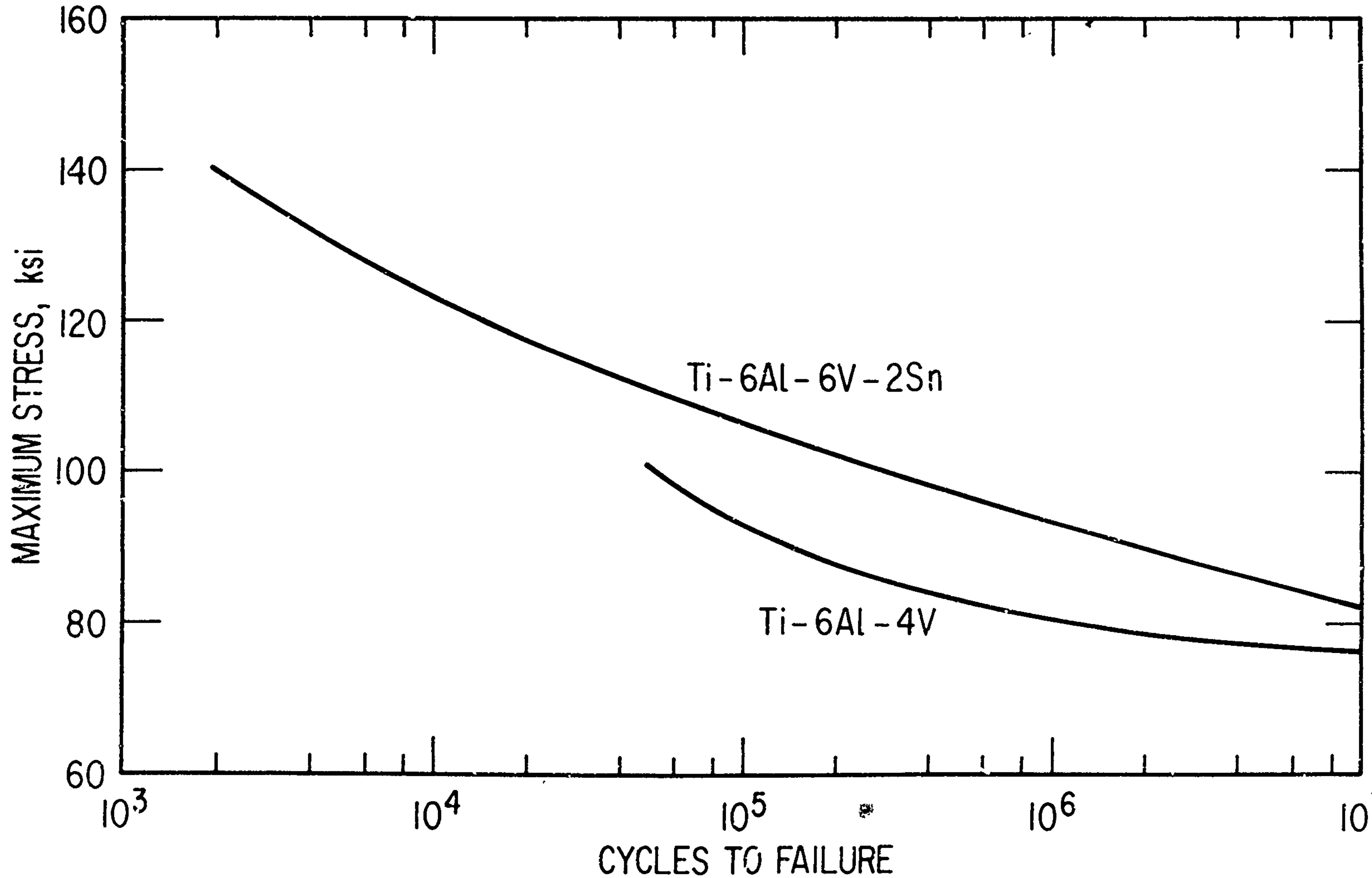


Fig. 69. Unnotched, S-N Behavior of Ti-6Al-4V STA Extrusions Compared With Ti-6Al-6V-2Sn (R = 0.1, Ref. 23)

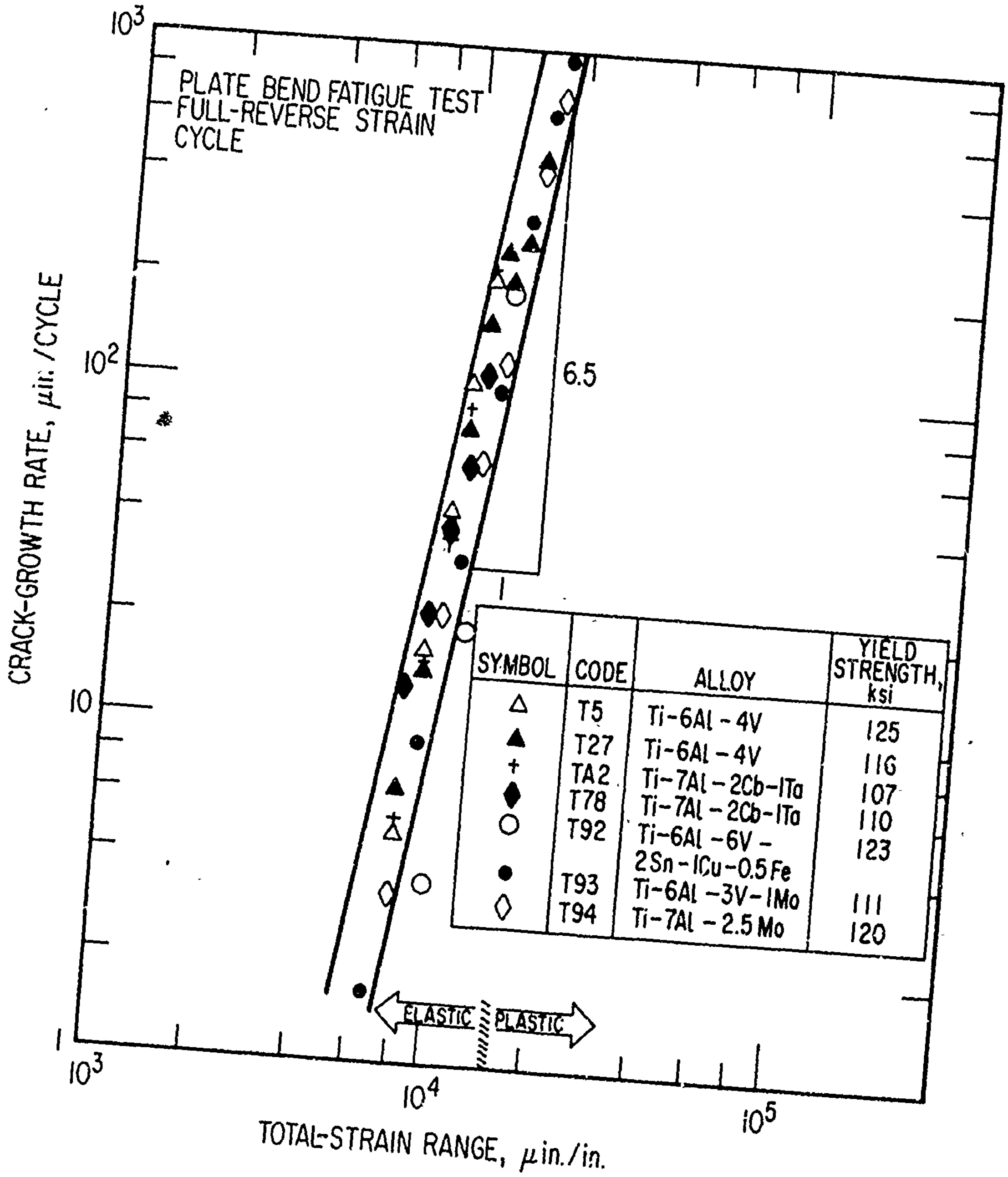


Fig. 70. Log-Log Plot of Crack Growth Versus Total-Strain Range for Titanium Alloys in an Air Environment (Material No. 36, Refs. 12 and 13)

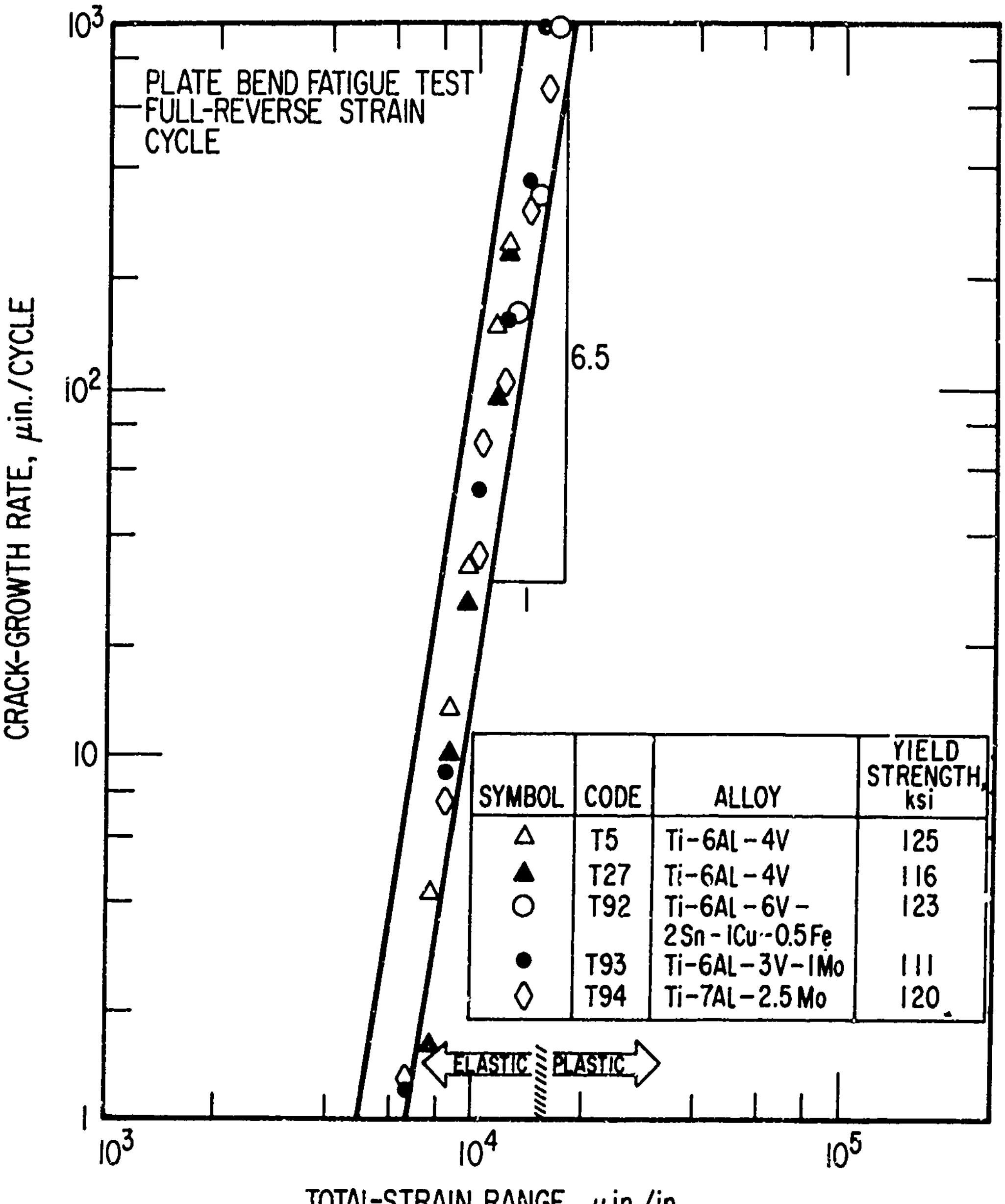


Fig. 71. Log-Log Plot of Crack Growth Versus Total-Strain Range for Titanium Alloys in a 3.5 percent Salt-Water Environment. (The scatter band limits are reproduced from the air environment data plot for reference.) (Material No. 36, Refs. 12 and 13)

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13. ABSTRACT

A compilation of Ti-6Al-6V-2Sn fatigue data is presented for a number of different material forms and conditions. Stress versus log cycles to failure (S-N) curves or master diagrams, or both, for annealed, solution-treated and aged (STA), and thermomechanically worked (TMW) materials are included. The data are organized according to material form, such as sheet, plate, rolled bar, forging, and extrusion. Crack propagation behavior in air and salt water is also included. The general characteristics istics of Ti-6Al-6V-2Sn fatigue are discussed and compared with those for other titanium alloys.

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Distribution Statement (Continued)

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